ESD whistlers from local Thunderstorms observed at Srinagar (L = 1.28) – First observation from Low Latitudes

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Abstract:

This paper reports the first observation of extremely small dispersion (ESD) whistlers from thunderstorms recorded during magnetic storm period at a low latitude ground station Srinagar (geomag. lat., 24⁰ 10' N; L=1.28). ESD whistlers with dispersion varying from 4-5 sec⁴/₅ surprisingly in large numbers were recorded on 06 April, 2011 at Srinagar during local thunderstorm period in the daytime afternoon. Such type of daytime ESD whistlers from local thunderstorm recorded during magnetic storm period at Srinagar has never been reported from any of the low latitude ground stations and is the first observation from low latitudes. Results of the study of the characteristics of daytime ESD whistlers from local thunderstorms observed at Srinagar shows that these whistlers are ducted whistlers and are found to obey perfectly the Eckersley law. Since the dispersion of these daytime ESD whistlers are found in the extremely small range of the order of 5 sec⁴/₅ which clearly shows that these whistlers have propagated over an extremely small path along the ducted field lines. It is proposed that daytime ESD whistlers from local thunderstorms recorded at Srinagar are the VLF waves radiated from the return stroke of lightning discharge present in local thunderstorms penetrated the ionosphere in waveguide mode and then they propagated to the other hemisphere along the geomagnetic field line of latitude ~ 5⁰ in whistler duct formed by the local thunderstorm electrostatic electric fields. After reaching the opposite hemisphere, these whistler waves again traverse in the waveguide mode to reach the observing station Srinagar. The generation and propagation mechanisms of these ESD whistlers observed during local thunderstorms are discussed.

Keywords: ESD whistler, VLF waves, Duct, Lightning discharge, Thunderstorm
1. Introduction

A thunderstorm, also known as an electrical storm, a lightning storm, or a thundershower, is a type of storm characterized by the presence of lightning and its acoustic effect on the Earth’s atmosphere. Thunderstorms are the deepest convective clouds caused by buoyancy forces set up initially by the solar heating of the Earth’s surface. Several field and laboratory experiments have been conducted to determine the electrical nature of thunderstorms and possible electrification processes are being studied in the laboratory and also through theoretical modeling and computer simulations (Rycroft et al., 2007; Krebhiel, 1986; Krebhiel et al., 2008). The most fascinating aspect of thunderstorm is lightning associated with it whose strength and location can be assessed by a number of techniques such as those involving electrostatic, electromagnetic, acoustic, radar and radio-frequency measurements. Lightning discharges in thunderclouds radiate powerful radio noise bursts over a wide frequency range from few Hz to several MHz. In the ELF/VLF frequency range, waves can propagate over long distances in the Earth-ionosphere waveguide. Waves in the very low frequency (VLF, 3-30 kHz) range penetrate the ionosphere and propagate along geomagnetic field lines in the dispersive plasma regions of the ionosphere and magnetosphere without appreciable attenuation. Thus the waves can propagate from one hemisphere to the other many times before being attenuated. The mode of propagation is called the whistler mode and the waves are termed whistlers. Whistlers are thus electromagnetic phenomena produced by the propagation of the radio energy from lightning discharges through the ionospheric and magnetospheric plasma. They are identified as audio frequency radio signals which usually begin at high frequencies (of the order of 10 kHz) and typically fall in frequency to 1 kHz or 2 kHz in about a second (Helliwell, 1965).

It is now well established that whistlers result from the penetration of lightning discharge-produced electromagnetic radiation through the ionosphere and magnetosphere (Helliwell, 1965). The geomagnetic field is not sufficient to guide the signal into the conjugate hemisphere and allow ground-based reception of whistlers in that hemisphere. But in fact, reception of whistlers in the conjugate hemisphere is generally common with the signals showing evidence of propagation along distinct field-aligned paths. It was, therefore, suggested that field-aligned ionization irregularities (ducts) might trap and guide whistler signals from one hemisphere to other (Smith et al., 1960; Helliwell, 1969). Ducts are regions of enhanced or depletion from normal ionization densities and hence have different values of refractive index from the surrounding plasma. Such irregularities have been observed using satellites (Angerami, 1970) and by highly sensitive measurements of signal delays on VLF transmissions (Thomson, 1975). Either enhancements or depleted regions of plasmaspheric plasma (cold) are capable of guiding VLF whistler waves in the required manner. The formation of field-aligned electron density irregularities (whistler ducts) by interchange of plasma in flux-tubes was first suggested by Cole (1971), who suggested that large-scale irregularities (conjugate ducts) arise due to the interchange of plasma in geomagnetic flux-tubes. The interchange is driven by a spatially varying electrostatic field (EXB) orthogonal to the geomagnetic field. Park and Helliwell (1971) have
suggested that the source of such electrostatic field might be charge centers in thunderstorms. The electrostatic fields from the thunderstorms penetrate the ionosphere and magnetosphere and causing mixing of electrons in flux-tubes around the equatorial plane. **EXB** forces as a whistler duct creation mechanism was first identified by Cole (1971). In the Cole model, irregularities in the E-region electron density lead to the orthogonal electrostatic field caused by variations in the ionosphere. Variability in the spatial wind in the dynamo region and gravity waves are suggested both producing ionospheric irregularities and hence irregular magnetospheric electric field. Walker (1978) has presented order of magnitude calculations to show that when the ring current overlaps in the outer plasmaspheric irregularities in the current cause field-aligned currents to flow down to the ionosphere. These currents would be continuous with horizontal electric field maps up into the equatorial region, producing flux-tube interchange, and once again the formation of whistler ducts. This mechanism would lead to duct formation on a time scale of 30 min, which would be expected to decay on a time scale of days (Walker, 1978). Thus, whistler duct is caused by plasma interchange of geomagnetic flux tubes driven by thunderstorm electrostatic fields (Park and Helliwell, 1971). At present, this is the most favored whistler duct creation mechanism. The best evidence for the plausibility of whistler duct creation mechanism from thunderstorms are the conclusion of Park and Dejankarintra (1973, 1977) where they have shown that giant thunderclouds are an important source of localized electric fields that can form field-aligned electron density irregularities in the ionosphere and magnetosphere.

The theory of trapping and propagation of whistlers in ducts have been discussed by several authors (Smith, 1961; Helliwell, 1965; Walker 1972; Liard and Nunn, 1975). The whistlers observed on the ground are generally assumed to have conformed to the ducted type of propagation through ionosphere and magnetosphere. This type of propagation is verified experimentally at middle and high latitudes (Angerami, 1970). The ducted mode of propagation for low latitude whistlers has also been favored by many Indian, Japanese and Chinese workers on the basis of ground observations, and they have studied the duct characteristics i.e. size, lifetime, separation etc. from the available whistler data (Somyajulu et al., 1972; Hayakawa and Ohtsu, 1973; Rao and Lalmani, 1975; Khosa et al.,1983; Lalmani, 1984; Hayakawa et al., 1985, 1990; Singh, 1993; Singh et al.,1998, 2013). Both the duct efficiency and scatter in the duct efficiency are observed to increase with \( K_p \). Both duct size and scatter in duct sizes increases with the increasing magnetic activity \( K_p \) and Duct efficiency increases by a factor of about 30 with \( K_p=2-8 \). These duct efficiency increase and their increased scatter could be due to plasmaspheric amplification resulting from enhanced magnetic activity increasing the range of anisotropy and particle energy fluxes. As the result of this, the transmission of whistler wave energy is found to increase as magnetic activity increased. An evidence of more efficient whistler-mode transmission during periods of increased magnetic activity has been observed by means of the whistler-mode signals received at Faraday, Antarctica (65°S, 64° W) and Dunedin, New Zealand (46°S, 171°E) (Thomson, et. al., 1997).
Since the pioneering work of Storey (1953), the observation of whistlers has been continued over a wide range of high-to-low latitudes (Allcock, 1960; Helliwell, 1965; 1969; Iwai and Ohtsu, 1956, 1958, 1962; Somayajulu et al., 1972; Rao and Lalmani, 1975; Hayakawa and Tanaka, 1978; Khosa et al., 1981; Lalmani et al. 1999, 2001; Singh et al., 1977, 1980, 2005, 2012). Later, at high, mid and low latitudes, both satellite and ground-based whistler data were exploited to reveal new facts about the structure and dynamics of the ionosphere and magnetosphere. These achievements included the discovery of the plasmaspheric, plasmapause, and bulge (Carpenter and Park, 1973), identification of the mechanisms of the ionosphere-protonosphere coupling (Park, 1970; Andrews, 1980, Lalmani et al., 1992, 1996, Singh et al., 1998), measurement of magnetospheric electric field (Carpenter et al, 1972; Misra et al, 1980; Lalmani et al., 1982) and electron temperature (Sazhin et al., 1990, 1992, 1993; Singh et al., 2008) etc. Further, a wide variety of whistlers recorded during day and nighttime at low latitude ground stations are markedly different from those recorded at middle and high latitudes. Whistlers in relatively large numbers at low latitudes are observed only during periods of high geomagnetic activity. Low latitude whistlers are characterized by a sharp occurrence peak in the daytime and a broad small maximum in the post -- midnight period. Daytime whistlers are found to appear during the very restricted hours in the afternoon. On the other hand, nighttime whistlers are observed over a wide time interval but generally peak in the early morning, and their dispersion is widely distributed (Somayajulu et al., 1972; Hayakawa and Ohtsu, 1973; Hayakawa et al., 1973; Lalmani et al., 2001; Singh and Hayakawa, 2001; Singh, 1993, 2007; Singh et al., 1977, 2005, 2012).

The daytime and nighttime whistlers are quite different from each other in respect of their different propagation mechanisms (Singh, 2007). In particular, much evidence has accumulated to indicate ducted propagation for the daytime whistlers at low latitudes. It is also suggested that the daytime whistlers are associated with the equatorial anomaly of the ionosphere (Hayakawa et al., 1973). Indirect evidence of ducted propagation of daytime whistlers has been observed by means of the simultaneous observations of a multistation network (Hayakawa and Ohtsu, 1973; Kohtaki et al., 1974). Hayakawa and Tanaka (1978) have made a comprehensive review of the propagation of low latitude whistlers, where they have clearly shown the ducted propagation for the daytime whistlers on the basis of not only observational but also theoretical studies. These previous investigations were all devoted to the analysis of frequency-time spectra of daytime whistlers observed during magnetically quiet and disturbed periods, but no reports have been published dealing with the detailed wave characteristics of daytime whistlers observed during local thunderstorm periods at low latitudes. Hence the formation and propagation mechanisms of daytime whistlers observed during local thunderstorm periods are not understood at low latitudes, though extensive work have been dealt with this subject at high latitudes (Park and Helliwell, 1971; Rodger et al., 1998; McCormick et al., 2002).
In order to obtain further understanding of the generation and propagation mechanisms of low latitude daytime whistlers and to supplement the earlier findings, we have carried out

Fig. 1: The frequency-time spectrograms of extremely small dispersion (ESD) whistlers recorded at low latitude Indian ground station Srinagar on 06 April, 2011 at (a) 14:35 IST, (b) 14:40 IST, (c) 14:45 IST, (d) 14:50 IST, (e) 14:55 IST and (f) 15:00 IST during thunderstorm and magnetic storm periods.

In order to obtain further understanding of the generation and propagation mechanisms of low latitude daytime whistlers and to supplement the earlier findings, we have carried out
whistler measurements at our newly installed ground-based Indian station Srinagar in the year 2009. Using standard whistler recording system at our field station Srinagar, we have observed entirely a new type of whistler with extremely small dispersion (ESD whistlers) on 06 April 2011 during local thunderstorm period in magnetically disturbed daytime in significant numbers. From the dispersion analysis of the daytime ESD whistlers from local thunderstorms recorded at Srinagar on 06 April, 2011 during magnetic storm period, it is found that all the whistlers have extremely small dispersion of the order of 5 sec$^{-\frac{1}{2}}$, and are found to obey perfectly Eckersly law. Such ESD whistlers observed during local thunderstorm period are ducted whistlers which can only be explained with the help of hybrid path propagation in waveguide and whistler duct. First observation of daytime ESD whistlers at Srinagar during local thunderstorm period provides an evidence of ducted propagation of daytime whistlers at low latitudes, in complete agreement with the earlier findings of ducted propagation of low latitude daytime whistlers.

The purpose of this paper is to present the results of ESD whistlers recorded on 06 April, 2011 in magnetically disturbed daytime during local thunderstorm period at our field station Srinagar. The generation and propagation mechanisms of these ESD whistlers from local thunderstorms have been discussed in detail.

2. Observations and Analysis

The present study is based on whistler observations made at our newly setup ground station Srinagar (L=1.28) in India from January 2009 to August 2012. The whistler mode signals are received by a T-type of antenna, amplifiers and tape recorder having band width of 50 Hz-15 kHz. T-type antenna is 25m in vertical length and 6m long horizontally and 3.2mm in diameter. Its impedance is about 1m$\Omega$. The antenna is rendered periodic with the help of suitable R-C network, to avoid any possible ringing effect. The antenna is erected at a suitable distance from the main building to reduce the power line hum and any other type of man made noises. Between the antenna and pre/main amplifiers an active filtering unit is introduced to reduce the local noise to a minimum in the frequency range 100 Hz-500 Hz. The filter is constructed from a suitable R-C network along with the operational amplifier to be operated in positive feedback mode. The lower cut-off frequency of the filter is about 60 Hz and voltage gain is 1.2 up to 15 kHz. In this recording setup we have not used anti-aliasing filter. The gain of the pre/main amplifiers is varied from 0-40 dB to avoid overloading of the amplifier at the time of great VLF activity. The observations were taken continuously both during day and night times. The VLF data were stored on the magnetic tapes, which were analyzed using a digital sonograph machine. Digitization of the analog signal was carried out at 16 kHz sampling frequency. The inbuilt software in the spectrum analysis of the sonograph machine provides dynamic spectrum, which updates in real time typically covering 8 KHz in frequency and 2.54 second in time. The frequency range may be varied from 100 Hz – 40 KHz.
Sample records of ESD whistlers observed on 06 April 2011 during local thunderstorm activity period in magnetically disturbed daytime hours are shown in Fig. 1a-f out of large collection of similar events recorded on this day. Fig. 1a-f illustrates single trace of short whistlers (W₁-W₆) of dispersions 5, 4, 4, 5, 4 and 5 sec respectively with distinct causative atmospherics marked by arrow head (↑). On 06 April 2011, the spurt in activity started around 14:00 IST (Indian Standard Time), lasting for about one hour, ending finally at 15:00 IST. During this period, about 30 ESD whistlers were recorded. Such types of ESD whistlers were observed only in local daytime thunderstorm activity period during sudden commencement of magnetic storm. The magnetic activity during a period of observation was disturbed (∑Kₚ=29-). These whistlers were recorded during local thunderstorm magnetic storm period 04-08 April, 2011 with minimum Dₘ-index=-72nT and maximum Kₚ-index= 5- on 06 April, 2011. Fig. 2

Fig. 2: Kp-index and Dst-index variation during magnetic storm period 04-08 April 2011. The time of occurrence of ESD whistlers recorded at low latitude Indian ground station Srinagar on 06 April, 2011 during local thunderstorm period is also marked by arrow head (ESD = Extremely Small Dispersion).
shows the variations of Kp-index and Dst-index during magnetic storm period. The observation period of ESD events at Srinagar are also marked in this figure. These were recorded in the afternoon period during main phase of the storm. The occurrence of this type of events from local thunderstorms during magnetic storm period seems to be rare and unique in the sense that such events have not been reported earlier from any of the low latitude ground stations.

For a spectral analysis, the normal procedure of analysis by means of sonographic equipment was used. Detailed spectral analysis has been made for ESD whistlers observed on 06 April 2011, in order to study their observational and propagational characteristics. From the detailed dispersion analysis, it was found that the measured values of all the recorded ESD whistlers on this day have extremely small dispersions lying only in the range of 4-5 sec$^{1/2}$ and lie in the frequency range between 2.8-7.2 kHz. The observed lower cut-off frequencies of these whistlers are well above the waveguide cut-off frequency 1.67 kHz. Table 1 shows the details of ESD whistlers recorded on 06 April 2011 during daytime local thunderstorm activity period at Srinagar. These ESD whistlers are generated precisely from the local thunderstorms occurred near the receiving station Srinagar. This is confirmed from the thunderstorm burst containing closely spaced number of atmospherics without any dispersion present in all the spectrograms of ESD whistlers as clearly seen in Fig. 1. These ESD whistlers is not originated due to thunderstorms occurred in the opposite hemisphere of the receiving station Srinagar because bursts of closely spaced atmospherics have no dispersion at all as clearly seen in Fig. 1. The temporal distribution of number of ESD whistlers observed on 06 April 2011 during local thunderstorm period is shown in Fig. 2. The occurrence rate peaks around 14:30 IST local time. This is in agreement with earlier results reported by Japanese workers at low latitudes (Hayakawa and Tanaka, 1978).

**Table 1: Details of ESD whistlers recorded on 06 April 2011 during daytime local thunderstorm activity period at Srinagar (L=1.2).**

| Day             | Time(IST) | Dispersion(sec$^{1/2}$) | Lower cut-off | Higher cut-off |
|-----------------|-----------|-------------------------|---------------|---------------|
| 06 April 2011   | 14:35 IST | 5.0                     | 2.8           | 6.3           |
| 06 April 2011   | 14:40 IST | 4.0                     | 3.5           | 7.2           |
| 06 April 2011   | 14:45 IST | 4.0                     | 3.1           | 6.6           |
| 06 April 2011   | 14:50 IST | 5.0                     | 3.4           | 6.9           |
| 06 April 2011   | 14:55 IST | 4.0                     | 3.2           | 6.9           |
| 06 April 2011   | 15:00 IST | 5.0                     | 3.2           | 6.8           |

3. Results and Discussions

It is clearly seen that good quality of ESD whistlers are recorded at Srinagar in daytime local thunderstorm activity period during magnetic storm period. 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 ESD whistlers observed during 06 April 2011 and have extremely small dispersion of the order of 5 sec$^{1/2}$ and are strictly found to obey Eckersley law, hereby indicated that presumably these whistlers had a quasi-longitudinal propagation with a right handed circular polarization. The normal dispersion values of whistlers observed at Srinagar should be about 29 sec$^{1/2}$ based on the minimum critical frequency of the F2-layer and the electron number density at the equatorial height of the geomagnetic line of force corresponding to Srinagar and from the regression line given by Hayakawa and Tanaka (1978) and also based on the Allcock’s formula (Allcock, 1960). The observation of such ESD whistlers during local thunderstorm period provides us strong evidence in support of ducted propagation of daytime whistlers at low latitudes. Table 1 shows the details of the dispersion analysis of ESD whistlers recorded in magnetically disturbed daytime hours during local thunderstorm period on 06 April, 2011 at Srinagar.

In order to arrive at the best plausible propagation mechanism for the explanation of ESD whistlers from local thunderstorms observed at Srinagar on 06 April 2011, some of the explanations of the earlier observed SP and ESD whistlers are cited below:

3.1 Observation of Sub-Protonospheric (SP) whistlers with their explanation:

SP whistlers with extremely small dispersion of the order of 5 sec$^{1/2}$ 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 ionospheric heights with increasing dispersions corresponding to the increase in number of reflections (Carpenter et al., 1964). One of the interesting features of SP-whistlers is that they are found to obey Eckersley law within the 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 sec$^{1/2}$. However, SP-whistlers are not observed at low latitudes even by satellites. Therefore, the possibility that ESD whistlers observed at Srinagar 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 Srinagar is not an even integer. Hence, possibility of occurrence of ESD whistlers with dispersions ranging from 4 to 5sec$^{1/2}$ may not probably be explained in terms of different SP-whistlers.

3.2 Earlier observation of ESD whistlers with their explanation

ESD whistlers have also been earlier observed at Japanese ground stations Kakioka (geomag. lat., 26° N) and Tohakatta (geomag. lat., 28° N) (Tsuruda et al., 1964; Araki and Kamiyama, 1969; Takuda, 1964). The field-aligned (ducted) propagation was suggested by Tsuruda et al. (1964) to explain ESD whistlers observed at Kakioka and Tohakatta Japan. They have speculated a hybrid
path (combined propagation paths of whistlers in waveguide and whistler duct) in which they assumed that the source region is around the magnetic equator and field-aligned mechanism is present at latitudes as low as 10°. According to their hypothesis the VLF waves radiated by the return stroke of lightning discharges propagate initially in 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 transverse in the waveguide mode to reach the observing station. Thus, they have adopted the hybrid path of whistler wave propagation to explain the occurrence of ESD whistlers observed at Kakioka and Tohakatta, Japan.

Ohtsu (1963) has also explained theoretically ESD whistlers with a small dispersion of 5 sec\(^{1/2}\) in terms of oblique propagation effect arising from the large angle between wave normal and geomagnetic field direction of low latitudes. Dikshit et al. (1971) have suggested that the low-dispersion nighttime whistlers (15 and 10 sec\(^{1/2}\)) 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. (1972), 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 (Dikshit et al., 1971).

Recently in the years 1998 and 1999, ESD whistlers with dispersions varying from 3-10 sec\(^{1/2}\) in significant numbers were recorded at low latitude Indian ground stations Jammu (geomag. lat., 22° 26’ N) and Bhopal (geomag. lat., 13°47’ N) in day and nighttimes during magnetically quiet and moderate periods. These ESD whistlers observed at Jammu and Bhopal has been explained in terms of non-ducted propagation (Lalmani et al., 1999; Singh et al., 2005). It has been proposed that these ESD whistlers recorded at Jammu and Bhopal are the VLF waves radiated from the return stroke of the lightning discharge launched at the ionosphere with different initial wave normal angles, propagated upwards under either quasi-longitudinal conditions or pro-longitudinal whistler mode, turned around at different heights due to quasi-transverse propagation and received at these low latitude stations with dispersions ranging from 3 to 10 sec\(^{1/2}\). The validity of this suggestion has been tested by Lalmani et al. (2001) from ray-tracing studies by performing actual ray-tracing computations in the presence of equatorial anomaly model. They have explained ESD whistlers observed at Jammu with the help of ray-tracing technique as advanced by Shawhan (1966) and have successfully explained the dispersion, lower and upper cut-off frequencies of these observed ESD whistlers and their dynamic spectrum.

Thus ESD whistlers earlier observed at ground-based stations Suffield and Great Whale River in USA, Jammu and Bhopal in India were explained on the basis of non-ducted whistler mode propagation (Carpenter et al., 1964; Okuzawa and Horita, 1974; Shawhan, 1996; Singh et al., 1972; Lalmani et al., 1999, 2001; Singh et al., 2005). On the other hand ESD whistlers observed
at ground stations Kakioka and Tohakatta in Japan were explained in terms of field-aligned (ducted) propagation by Tsuruda et al. (1964). They have attributed the recording of these whistlers to the hybrid paths followed by the whistlers as discussed in detail earlier.

3.3 An explanation of the reported daytime ESD whistlers from thunderstorms observed at Srinagar:

ESD whistlers presented in this paper have been recorded in magnetically disturbed daytime during local thunderstorm activity period on 06 April 2011 at our newly setup ground-based Indian station Srinagar. Since these whistlers have been recorded during local thunderstorm period, it clearly means that the source of these whistlers are lightning discharges present in the local thunderstorms occurred on this day of observation, as evident from the thunderstorm atmospheric bursts clearly seen in the whistler spectrograms in Fig 1. The originating (causative) atmospherics among the closely spaced thunderstorm atmospheric bursts of the observed ESD whistlers are shown in Fig. 1 by the arrow head (↑). These whistlers are produced by the propagation of VLF waves radiated from the return strokes of local thunderstorm lightning discharges through the whistler duct created by the local thunderstorm electrostatic fields occurred on 06 April 2011. After reaching the opposite hemisphere by propagating through whistler duct formed by local thunderstorms, these whistler waves again traverse in the waveguide mode to reach our observing station Srinagar. Thus, the observation of daytime ESD whistlers during local thunderstorm period in magnetically disturbed day on 06 April 2011 at Srinagar gives an experimental evidence of being ducted whistlers. Since ESD whistlers observed at Srinagar are ducted whistlers with extremely small dispersions of the order of 5sec\(^{1/2}\), it clearly means that these ESD whistlers from thunderstorms with dispersion of \(\sim 5 \text{ sec}^{1/2}\) have travelled a very small path in the whistler duct formed by the local thunderstorm electrostatic fields. This is possible only when the VLF waves radiated from thunderstorm lightning discharges penetrate the ionosphere at geomagnetic latitude of the order of 5° and then propagate along the field line of this latitude in whistler duct formed by the local thunderstorm electrostatic fields. After propagating along this ducted latitude, these waves exit from the same latitude of 5°. Thus, observations of ESD whistlers from local thunderstorms of dispersion of the order of 5sec\(^{1/2}\) at Srinagar can be explained successfully in terms of field-aligned (ducted) mode of whistler propagation.

The above value of exit propagation path latitude of about 5° of ESD whistlers with dispersion of the order of 5 sec\(^{1/2}\) recorded at Srinagar, has been estimated by a number of methods (Hayakawa and Tanaka, 1978; Tarcsai, 1975; Park, 1978). The propagation path of whistlers is determined by measuring the exit path of the whistler wave. In the absence of such measurements, the same is determined by determining the exit propagation path latitude of whistler wave, which is evaluated from the empirical relation between dispersion and geomagnetic latitude of whistler propagation.

\[
D = 1.22 (\phi - 0.72) \quad (1)
\]
where D is measured dispersion of whistler in sec$^{1/2}$, obtained from the slope of $t$ verses $f^{-1/2}$ plot in which time delay $t$, whistler wave frequency $f$ is measured from the spectrogram of the observed whistlers and $\phi$ is the geomagnetic latitude in degrees. This relation is given by Hayakawa and Tanaka (1978) based on the whistler data obtained at the Japanese ground stations. Using this relation (eq.1) the computed exit propagation path latitude of our observed thunderstorm ESD whistlers having dispersion of the order of 5 sec$^{1/2}$, is found to be of $\sim 5^0$.

Although, this method of the determination of propagation path latitude of whistlers gives good results at low latitudes, its validity may be questioned. To examine its validity, we have analyzed daytime ESD whistlers from thunderstorms recorded at our ground station Srinagar in magnetically disturbed daytime during thunderstorm activity period, using the curve fitting technique developed by Tarcsai (1975) and the method of Dowden-Alcock linear extended Q-technique for the determination of exit propagation path latitude. It is to be noted that both these techniques have been applied successfully in the past to the low latitude whistlers whose
propagation paths are below $L = 1.4$ (Khosa et al., 1990; Singh, 1993; Lalmani et al., 1992, 1996; Singh et al., 1999, 2000, 2004, 2006). Both methods yielded results within ±10 percent to that determined value of exit propagation path latitude using empirical relation given by Hayakawa and Tanaka (1978).

On the basis of above experimental results, we have developed a best plausible ducted model for the generation, propagation and reception of whistlers to explain the daytime ESD whistlers from local thunderstorms observed on 06 April 2011 during magnetic storm period at Srinagar in the light of suggestion made by Tsuruda et al. (1964). The schematic diagram of our developed model is shown in Fig. 3. According to our developed model, the VLF waves radiated from the return strokes of lightning discharges in the local thunderstorms propagate initially in the waveguide mode from their source and later penetrate the ionosphere in whistler mode. Then they propagate to the opposite hemisphere along the geomagnetic field line of latitude $5^\circ$ in whistler duct formed by local thunderstorm electrostatic fields. After reaching the opposite hemisphere by propagating in whistler duct along the latitude of the order of $5^\circ$, they again penetrate the ionosphere and then traverse in the waveguide mode to reach the observing station Srinagar. In our developed model we have adopted the combined propagation paths of waveguide mode and whistler ducted mode (hybrid path) as suggested by Tsuruda et al. (1964) in order to explain the occurrence of daytime ESD whistlers from local thunderstorms during magnetic storm period observed at Srinagar. It is quite clear from the characteristics of the ESD whistlers observed at our ground station Srinagar during local thunderstorm period that the source of these whistlers is the local thunderstorms occurred on 06 April, 2011. In our developed model the source region of these whistlers is around our observing station Srinagar (24$^\circ$ 10' N) and the field-aligned mechanism (whistler-duct formation due to thunderstorm electrostatic fields) is present at latitudes as low as $5^\circ$. Since these whistlers were observed during magnetic storm period which increases the efficiency of duct formed by thunderstorm electrostatic fields. Therefore, the transmission of whistler wave energy through the duct formed by local thunderstorm electrostatic fields was enhanced during magnetic storm period 04-06 April 2011.

Thus our simplified model explains very well about the occurrence and dispersion characteristics of daytime ESD whistlers from local thunderstorms with dispersion of the order of 5 sec$^{1/2}$ during geomagnetic storm period recorded at Srinagar. From the results and discussions, it is concluded that ESD whistlers from local thunderstorms observed on 06 April 2011 in daytime during magnetic storm period are ducted whistlers in well agreement with the earlier findings of ducted propagation of low latitude daytime whistlers. Such fine structure in dispersion of daytime ESD ducted whistlers recorded at Srinagar is rarely seen in the ground data and our result is very significant in this context.

4. Conclusions

This paper presents interesting and important observations of ESD whistlers from thunderstorms based on the long term data collected during daytime at a low latitude Indian ground
station Srinagar. These ESD whistlers are from local thunderstorms observed on 06 April 2011 during magnetic storm period in the daytime afternoon sector. The magnetic activity during the period of observation was disturbed ($\sum Kp=29$). The ESD whistlers presented in this paper are unique in the sense that this is the first observation of daytime ESD whistlers from local thunderstorms during magnetic storm period at low latitudes. The dispersion analysis of these ESD whistlers shows that the dispersion of these whistlers are extremely small in the range of 4-5 sec$^{1/2}$ and are found to obey perfectly the Eckersley law. The dispersion and propagation characteristics of these ESD whistlers recorded during local thunderstorm period are successfully explained through a mechanism model developed by us in the light of the hypothesis given by Tsuruda et al, (1964). Results of this study show that these ESD whistlers from thunderstorms are ducted whistlers in well agreement with the earlier findings of ducted propagation of low latitude daytime whistlers. Our observations of daytime ESD whistlers from local thunderstorms during magnetic storm periods gives an evidence of the formation of whistler ducts due to the plasma interchange of geomagnetic flux tubes driven by thunderstorm electrostatic fields, a most favored whistler duct creation mechanism. Our results naturally account for the essential features of daytime ESD whistlers as a ducted whistlers observed during local thunderstorm periods in magnetically disturbed day. This experimental study is unlikely to be the final word on the origin and propagation mechanism of these events and further experimental confirmation will, of course, be required at low latitudes. For this a large database needs to be generated along with substantial theoretical investigation to substantiate our viewpoint.

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