Unusual sferics observed at Agra

Uma Pandey, Anubha Bajpeyi, Madhurima Mishra, Abhishek Sharma & Birbal Singh
Department of Electronics and Communication Engineering, R B S College, Bichpuri, Agra 283 105
E-mail: bbbsagra@gmail.com

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Employing the experimental setup intended for whistler observations, a large number of unusual sferics have been recorded at the low latitude ground station Agra (geomagnetic latitude 18.09°N, longitude 152.21°E) during six months of observations between 01 November 2009 and 30 April 2010. The data include banded and narrow band sferics whose occurrences are found to be enhanced occasionally. The results have been examined as possible effects of lightning, solar flare, magnetic storms, and earthquake. The unusual enhancement of all types and those of banded structures have been found to correlate positively with X-ray events and magnetic storms, respectively. The banded and unusual structures of sferics have been interpreted in terms of specular reflection from a slab of enhanced ionization existing at the base of the ionosphere.

Keywords: Banded sferics, Narrow band sferics, Lightning, Solar flares, Magnetic storm, Specular reflection

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1 Introduction

The electromagnetic energy radiated from lightning discharge is spread over a wide range of frequency spectrum ranging from ultra low frequency (ULF) to high frequency (HF). However, the peak energy is concentrated in very low frequency (VLF) range of 5 - 10 kHz. While a part of the VLF energy penetrates the ionosphere to propagate in whistler mode, the other part propagates to long distances through earth-ionosphere space and on being recorded and heard through simple electronic equipments, sounds like ‘click’ known as atmospherics or sferics. Since all the frequency components of the sferics travel with the same velocity in the non-dispersive sub-ionospheric space, they arrive at the receiver at the same time and appear as vertical lines on the frequency-time spectrograms. They may also show a small dispersion at lower frequencies due to partial propagation in the ionosphere and appear as ‘tweeks’. The studies of sferics and tweeks are very useful in determining the location of the causative lightning discharges and the characteristics of the lower ionosphere. A detailed description of the early studies on sferics and tweeks has been presented by Helliwell. Later on, several researchers have made useful contributions on the theory and application of sferics and tweeks.

Banded structure in whistlers was reported first from the Orbiting Geophysical Observatory (OGO 4) satellite observation in which one or more bands of frequencies were missing from the whistler spectrum. It was suggested that the banded structure was caused by interaction of plane electromagnetic waves traveling in anisotropic plasma with a field-aligned slab of enhanced ionization above the altitude of the satellite. Later on, Somayajulu and Tantry reported banded structure of whistlers and sferics from the analysis of the data obtained from observations at the low latitude ground station Nainital. Singh et al. and Singh & Singh have attempted to explain these new whistler characteristics in terms of specular reflection from sporadic-E layers (Es layers) while propagating towards ground.

Recently, nighttime (1800 – 0600 hrs LT) observations for whistlers and VLF emissions have been carried out at Agra (geomagnetic latitude 18.09°N, longitude 152.21°E) for a period of six months from 01 November 2009 to 30 April 2010 and a large number of normal and unusual sferics have been recorded which show narrow frequency bands of occurrence and banded structure. The occurrences of unusual sferics have been found to be considerably enhanced occasionally. The effects of lightning, solar flares, magnetic storms and earthquakes on the occurrence characteristics of the sferics have been examined. It has been observed that their propagation is influenced by solar flares and magnetic storms. The unusual structures have been interpreted in the light of
results of Singh et al.\textsuperscript{13} and Singh & Singh\textsuperscript{14} who have interpreted similar observed characteristics in low latitude whistlers.

2 Experimental set up

The experimental set up developed at Agra, for recording of sferics and whistlers, has been shown in Fig. 1, which is similar to Singh et al.\textsuperscript{15} with some modifications. This is a modified version of the conventional recorder used extensively at various whistler ground stations in India. The system consists of a vertical antenna (instead of a loop antenna used by Singh et al.\textsuperscript{15}), preamplifier, 10 kHz low pass filter, sound card, and a PC (with sound recording software). The gain of the amplifier is 40 dB with flat frequency response in the audible range. The amplified signal is passed through a band pass filter (2-10 kHz) and recorded on a PC through the sound card. The sampling rate used for the present study is 20 kHz. It may be noted that the sound card used here corresponds to a frequency of 22 kHz so that as per Nyquist’s criteria the observations could be taken for frequencies less than 10 kHz. A freeware (Jet Audio) software is used to transfer the acquired data from sound card buffer to hard disk.

3 Solar flare (X-ray), Earthquake, Magnetic storm, and Lightning data

It has been mentioned above that sferics can travel large distances (~ 10,000 km) in sub-inospheric space after reflections from the earth and lower boundary of the ionosphere. It is possible that during such long propagation they may arrive at the study station (Agra) at night from dayside of the earth where thunderstorm activities are in progress. In that case, X-ray emission from solar flares can influence the structure of the dayside D-region ionosphere. It is known that during an X-ray flare, the electron density in D-region increases by 7-35 times as a result of which the reflection coefficient of the ionospheric boundary of the earth ionosphere waveguide is increased\textsuperscript{16}. Hence, the sferics propagation to this study station may carry the information of both the day and nighttime ionosphere. Keeping this in view, the sferics activity has been examined at the study station in relation to solar flare (X-ray) data which are taken from the National Oceanic and Atmospheric Administration’s National Weather Service website (http://www.swpc.noaa.gov).

There are ample evidences that electromagnetic emissions are generated in wide frequency range from ultra low frequency (ULF) to high frequency (HF) form earthquake regions and propagated to the atmosphere, ionosphere and magnetosphere [refs (17-18) and references therein]. It has been found that naturally occurring VLF pulses (f = 1-9 kHz) are enhanced considerably prior to the occurrences of Kurile and Kobe earthquakes in Japan\textsuperscript{19-20}. Since sferics frequencies considered here lie in the similar range (0-10 kHz) as those of VLF pulses considered by Japanese researchers, it is worthwhile to examine the effect of earthquakes on sferics activity also. The earthquake data considered for this purpose have been taken from the United States Geological Survey website (http://www.neic.usgs.gov).

Further, it is known that the energetic neutral particles resulting from ring current ions of energy 1-200 KeV as a result of charge exchange mechanism during magnetic storms hit the lower ionosphere and cause significant precipitation. Lyons & Richmond\textsuperscript{21} have emphasized that the nighttime E-region ionization enhancement at low latitudes during magnetic storms is due to this reason. Voss & Smith\textsuperscript{22} have discussed global zones of particle precipitation and suggested that precipitation below ± 20° latitudes may well be attributed to charge exchange of ring current particles. Jain & Singh\textsuperscript{23} have shown that the daytime E-region ionization enhancement during magnetic storms may also be attributed to this mechanism. The localized E-region ionization enhancement during magnetic storms may be attributed to this mechanism. The localized E-region ionization enhancement during nighttime may influence the sferics propagation to the study station and hence the effects of magnetic storms on sferics activities have also been studied. The magnetic storm data has been taken from World Data Center for Geomagnetism, Kyoto website (http://www.neic.usgs.gov).

Finally, recent investigations have shown localized heating and ionization enhancement at the base of...
lower ionosphere due to lightning and sprites which are known to influence the sub-ionospheric propagation of fixed frequency VLF transmitter signals\textsuperscript{24-26}. Such ionization enhancements may also influence the propagation of sferics in the earth ionosphere waveguide. In order to examine this possibility, lightning data within 200 km from Agra station has also been considered. This data has been taken from Weather Underground website (http://www.wunderground.com).

### 4 Results and Discussion

Agra station has been known for whistler studies for a long time. Recently, Department of Science and Technology, Government of India has sanctioned a research project to this station for carrying out ionospheric and magnetospheric studies at low latitudes using whistler technique. As a part of this project, routine observations of sferics and whistlers have been started from 01 November 2009 and continued up to 30 April 2010. This period covered most of the whistler season which existed between the months of October 2009 and April 2010. The nighttime (1800-0600 hrs LT) observations were carried out at Bichpuri, a rural area about 13 km west of Agra city, where local electric and electromagnetic disturbances are low. The day-to-day data has been analyzed using the technique suggested by Singh et al.\textsuperscript{15} in which MATLAB software was extensively used for noise filtering, calculation of FFT, making a movie of whole data set, and then preparing 6 sec frames of data saved as AVI movie file for visual observation. An interesting result has been found from analysis of the bulk of data is that sferics activities are enhanced considerably on one or two occasions as compared to normal days during the six months of observations. Further, the data included unusual sferics which showed banded structure and narrow bands of occurrence. The frequency spacing between the bands may be regular or irregular. Similarly, lower and upper cut off frequencies of the narrow band sferics may also vary from event to event. The examples of banded sferics with regular and irregular bands have been shown in Fig. 2 (a-b). The date and time of observations have been given on the top of the figure. Upward arrows on the time scales show the occurrence of unusual sferics. While Fig. 2a shows the sferics with regular bands having frequency spacing of 200 Hz, Fig. 2b shows a sferics of 09 irregular bands with frequency spacing varying in the range 300-500 Hz. An interesting observation that can be made from the spectrum of the banded sferics is that it has ELF components. Such sferics results from strong lightning activities and propagates in quasi transverse electromagnetic mode (QTEM) of propagation confined to the region of causative lightning discharges. Figure 3(a-b) shows the examples of narrow band structures. While Fig. 3a shows the spectrum of the sferics between 2.4 and 4.3 kHz, Fig. 3b shows the same between 2.9 and 5.4 kHz.

![Fig. 2—Banded sferics: (a) regular bands with missing frequencies of about 200 Hz; (b) irregular bands with missing frequencies between 300 and 500 Hz](image-url)
These sferics have not been found to be associated with whistlers but occurred in the same months of March - April in which earlier unusual sferics and whistlers were recorded by Somayajulu\textsuperscript{11} and Tantry\textsuperscript{12}.

The unusual occurrence of banded and narrow band structures in sferics can not be attributed to either instrumental effect or to local noise because several sferics occurred without such structures in the same night of observations. An example of a normal sferics recorded during the same night of observation as some of the banded sferics on 08 April 2010 has been shown in Fig. 4(a-b). The observations have been made using broad band vertical antenna installed over the roof of a double storey building. Normal sferics recorded on the same night of 08 April 2010 as that of banded sferics. The possibility that the occurrences of nulls in the sferics spectrum are caused by destructive interference of signals from multiple stroke lightning is also ruled out because there are many sferics with irregular bands and unusual lower

Fig. 3—Narrow band sferics in frequency range: (a) 2.4 - 4.3 kHz; (b) 2.9 - 5.4 kHz

Fig. 4—Normal sferics recorded on the same night of 08 April 2010 as that of banded sferics
and higher cut off frequencies. Lastly, the possibility that the banded structures occur due to banding in the source spectrum itself is untenable primarily because all sferics do not show banded structures, and secondly occurrence of banded structures in the source spectrum (lightning) has never been observed and reported.

The effects of some geophysical phenomena on the propagation characteristics of sferics have been examined. In the top panel of Fig. 5, the results of the statistical study of the occurrence pattern for banded sferics have been shown. The three thick horizontal lines show the mean ($m$) and standard deviation around the mean ($m \pm \sigma$). The dark solid circles show the occurrence days of lightning within 200 km around Agra. The lightning data have been shown because there are ample evidences of localized ionization caused in the mesosphere and ionosphere due to the heating by instance X and Gamma rays and quasi-electrostatic fields originated from thunderstorms and lightning activities $^{24-29}$. However, the lightning activities here do not appear to influence the enhanced sferics activities on 7 April for the reason that such perturbations last on shorter time scale of 10-100 sec. though the effect of lightning around Agra has been found to influence the sub-ionospheric propagation of VLF signals $^{30}$. In the lower panel of the figure, the variation of $\Sigma K_p$ for the same period of data analysis has been shown. It has been found here that the enhanced occurrence of banded sferics on 7 April 2010 coincided with the enhanced $\Sigma K_p$ during 5-7 April indicating, thereby, that the propagation of this type of sferics is, indeed, influenced by magnetic storms. The question of how the magnetic storms can cause the enhancement and banded structures in sferics may be answered in the light of nighttime E-region ionization enhancements at low and equatorial latitudes ($L<1.2$) due to precipitation of ring current particles under charge exchange mechanism as explained above. Such enhanced ionization may cause the lower ionospheric boundary to be sharper and hence, increase the number of reflected sferics at the receiver.

Figure 6 is divided into three panels. The top panel is similar to the top panel of Fig. 5 but it includes all type of sferics, i.e. normal, banded and narrow band sferics. The enhanced occurrence on 20 January is predominantly due to normal type of sferics. The middle panel shows the variation of average X-ray intensity. The X-rays are well known to strike the lower ionosphere during solar flares and cause additional ionization $^{16,31,32}$ during daytime. The bottom panel shows the variation of earthquake activities ($M \geq 4.5$) within a radius of less than 2000 km from

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**Fig. 5**—(top) Statistical distribution of observed banded sferics over six months period; (bottom) Variation of magnetic storm ($\Sigma K_p$) during the same period
Agra station. The earthquake data have been shown because there are recent evidences of earthquake induced electric fields penetrating the ionosphere and creating ionization anomalies in the lower ionosphere which can influence the subionospheric propagation of VLF waves.

However, as seen from the figure, it is only the enhanced average X-ray intensity during 15-20 January (especially on 19 and 20 January) that coincide well with the enhanced sferics activity on 20 January indicating that there may be an intimate relation between the two. As mentioned earlier, the intense X-rays may penetrate down to the lower ionosphere and create ionization enhancement which may influence the subionospheric propagation of VLF waves.

Once the reasons for enhancements in occurrence of banded and normal sferics are known from Figs (5 and 6) in the light of magnetic storms and X-ray intensity, the question arises how the banded structure occurs in sferics. In order to answer this question, the work of Singh et al.\textsuperscript{13} and Singh & Singh\textsuperscript{14} may be referred to, who have assumed sporadic-E layer in the form of a field-aligned slab of enhanced ionization and calculated reflection coefficients for different whistler frequencies incident on the slab from below by varying the slab thickness, enhancement of ionization inside the slab (enhancement factor), and incident angle, etc. In that way, they interpreted the band structure of whistlers recorded at Nainital ground station. A similar irregularity has been assumed at the base of the ionosphere created during magnetic storm and various frequencies of the sferics incident on it from below during their waveguide mode propagation. In Fig. 7, the reflection coefficient vs frequency curves of Singh & Singh\textsuperscript{14} (Fig. 3) has been reproduced which has been obtained from a full wave calculation employing a slab thickness of 2 km.
enhancement factor 4, incident angle 80°, and location 19° latitude at 120 km height. In order to compare the band spacing and band numbers obtained from the sferics data with those deduced from Fig. 7, first the band numbers (number of observed bands) in the observed spectrum from below have been counted and their corresponding band spacing (frequency range in which each of them appear) has been determined. Then, the same has been determined from 08 maxima of Fig. 7 at the reflection coefficient of 0.5. The results of comparison have been shown in Fig. 8. It has been found that there are close correlations between the two. Hence, the banded structure in sferics may be interpreted in terms of specular reflection from ionization anomalies created in the lower ionosphere during magnetic storms. In a similar manner, the narrow band characteristics of sferics may also be interpreted in the light of results of Singh et al.\textsuperscript{13} who have shown that reflection coefficients vs frequency curve transforms into bell-type at certain slab parameters and incident angle.

5 Conclusions
The whistler recording equipments employing a vertical antenna have been operated for a period of six months between 01 November 2009 and 30 April 2010 at Agra station and a large number of normal and unusual sferics have been recorded. The unusual sferics show banded structure and narrow band characteristics. The occurrence of both normal and unusual sferics is found to be enhanced occasionally which are interpreted in the light of enhanced X-ray emissions and magnetic activities, respectively. The banded and narrow band characteristics are interpreted in terms of specular reflection from ionization anomalies in the form of a slab located at the base of the ionosphere at 120 km and sferics signals of different frequencies incident on it from below at large angle.

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