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Anomalous behavior of D-layer formation time of the ionosphere due to earthquake

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The very low frequency (VLF) data for over three months (May to July 2008) using Gyrator II loop antenna has been analyzed in the present study. The significant anomalies of D-layer formation time of the ionosphere are observed during sunrise. These anomalies are observed only before, during and after the earthquakes, which took place in the neighboring region. The anomalies were also observed in sunrise terminator time during seismically active days. These abnormal behavior may be due to the lithosphere - ionosphere coupling. These anomalies may be a precursor of earthquake.

Keywords: Radio wave propagation, D-layer, Ionospheric disturbances, Earthquake

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1 Introduction

An earthquake results when tectonic plates get stuck releasing energy stored in the earth's crust. It manifests itself by a shaking or movement of the surface of the earth, sometimes causing a tsunami. The earthquake prediction is the prediction that an earthquake of a specific magnitude will occur in a specific location at a specific time within a stated uncertainty bounds. Research works on earthquake precursors have a long history and several methods of prediction, viz. earthquake weather, arrangement of planets, tidal forces, unusual animal behavior, etc., have been evolved. But all these are unreliable and unsuccessful. In 1960s extensive research work has been initiated on earthquake prediction especially in seismically active countries like Japan, China and Russia. Out of all precursory methods that have come up in the literature, the ionosphere precursors of earthquakes are the latest.

There are a number of evidences that electromagnetic phenomena take place in a wide frequency range (ULF, VLF, LF) prior to an earthquake[1-5]. Although the first attempt of VLF sounding due to seismo-ionospheric effects was done by Russian scientists[6,7], the most convincing result was obtained by Hayakawa *et al.*[8] for the Kobe earthquake of 1995. Singh *et al.*[9] presented very low frequency electric field perturbations using borehole and terrestrial antennas associated with Chamoli earthquakes occurred during March-April 1999. They observed that electric field perturbations started 16 days prior to an earthquake. The study of ultra low frequency (ULF) emissions associated with seismic activities during moderate earthquakes in Satara and Ratnagiri (Maharashtra, India) in April-May 2006 was reported by Sharma *et al.*[10] They showed that temporal variation in the intensity of magnetic field at 0.1 Hz can be used as the precursory signature of an earthquake.

Many countries in the world operate large VLF transmitters mainly for navigation and communication with military submarines. The electromagnetic energy radiated by a VLF transmitter is trapped between the ground and the lower ionosphere forming the earth-ionosphere wave-guide. The sub-ionospheric VLF signals are reflected back by the lowermost region of the ionosphere. During the nighttime, it is the E-layer that reflects the VLF waves but in the daytime, the D-layer reflects the signals. So any change in the reflecting region of the ionosphere leads to corresponding change in the propagation of the VLF signal through the earth-ionosphere wave-guide. The observed perturbations in the amplitude and phase of the VLF transmissions are caused due to different kinds of sources like solar flares, gamma-ray bursts, strong pulsars, impacts of meteors, lightning, geomagnetic storms, etc. In addition to these effects, one more effect has been suggested, i.e. the effect of earthquake or seismic activities on the lower ionosphere. Much before an earthquake takes place, the following processes could start causing ionospheric anomalies: (i) electric discharge during tectonic plate movements; (ii) variations in the electric field, which causes heating of the ionosphere; (iii) oscillation of magnetic field, which causes generation of VLF signals; (iv) discharge of radioactive radon gas, which decays and increases the ionization of ionosphere; (v) emission of earthquake lights, sonoluminiscence, triboluminisence, etc.

It is recognized that ionosphere is very much sensitive to the seismic effects. So the detection of ionospheric perturbations associated with earthquakes by monitoring VLF propagation through the earth-ionosphere wave-guide has been a very useful tool for the prediction of earthquakes. There are two methods of VLF data analysis for understanding seismo-ionospheric perturbations. One is nighttime fluctuation method in which the nighttime amplitude and/or phase anomalies are studied to see the correlation between seismic activities and ionospheric disturbances. The second one is the terminator time method and it is about determining characteristic times of minima in diurnal amplitude/phase variations during sunrise and sunset[8,11,12]. Chakrabarti *et al.*[13] used this method to interpret the results of data analysis of VLF signals at 17 kHz prior to Sumatra earthquake on 26 December 2004. Chakrabarti *et al.*[14] showed the unusual behavior of D-region ionization time during seismically active days. In this paper, the results of sub-ionospheric VLF perturbations at a frequency of 18.2 kHz are presented by analyzing data obtained from May to July 2008 during earthquakes in different parts of India and China.

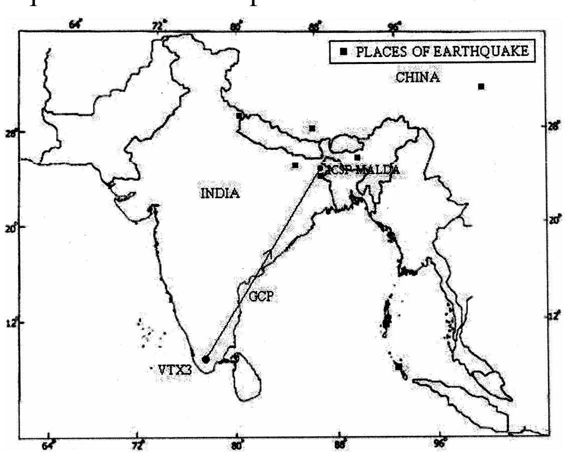

Fig. 1—Great Circle Path (GCP) drawn between the transmitter and the receiver and the approximate locations of earthquakes

2 Experimental setup

A Gyrator II loop antenna made on a square frame of one-meter side has been used. Several turns of a shielded single core wire are wound over the frame. This antenna is situated at a height of about 12 m from the ground at Malda (25°N, 88.8°E) branch of Indian Centre for Space Physics (ICSP). It receives VLF signal from VTX3, Indian Navy Traffic Station at Vijayanarayanam (8.26°N, 77.44°E) (Fig. 1). The antenna is tuned at 18.2 kHz. The gain of the receiver is set at a value 600 when there is no signal. A current is induced in the antenna by the magnetic field of the VLF signal. It is then amplified and fed into the audio card of a computer located inside the laboratory. The Radio-Sky Pipe software has been used for data acquisition.

3 Observations and data analysis

Figure 2 shows the general nature of the amplitude variation of VLF data obtained on 15 May 2008. and is the same for all other days. The nighttime variations in the amplitude are mainly due to scintillation effects but effects of solar radiation on the ionosphere cause daytime variations. During sunrise, the amplitude reaches a minimum at a particular time. This time is called the sunrise terminator time T_2 (Fig. 2). It is observed to be slightly greater than the local sunrise time. The effect of sunrise starts from a point of time represented by T_1 (Fig. 2) from where the amplitude starts to fall down very sharply up to the sunrise terminator time. This time T_1 represents the beginning of formation of the D-layer and the difference of time (T_2-T_1) is the D-layer formation time (DLFT).

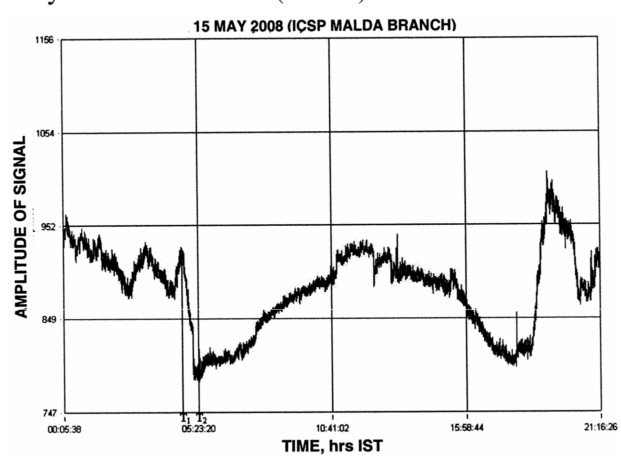

Fig. 2—General nature of VLF data: T_2 represents the sunrise terminator time; ($T_2 - T_1$) is D-layer formation time (DLFT)

The VLF data obtained for a period of three months, from 14 April to 14 July 2008 has been analyzed in the present study. During this time, several earthquakes occurred on different dates in India and its adjoining region (http://www.imd.ernet.in). The details of these earthquakes are given in Table 1. The anomalies are seen in the sunrise terminator time and the D-layer formation time before, during and after the days of earthquakes (Table 1). The places of earthquakes are close to the Great Circle Path (GCP) drawn from the transmitter to the receiver (Fig. 1). The ionosphere above the GCP is perturbed due to seismic activities and the result of this perturbation is manifested in the form of observed anomalies in the present VLF data.

The sunrise terminator time and the proper sunrise time against the day number of the year 2008 have been plotted in Fig. 3. Up to 128th day (7 May 2008), the sunrise terminator time, is as it is expected during otherwise quiet days, but afterwards, becomes anomalous. If Table 1 and Fig. 3 are seen side by side, it is seen that the sunrise terminator time becomes fluctuating two or more days prior to an earthquake and continues to be so for few more days after the earthquake. The maximum variation of 29 min 51 s from the undisturbed level is observed during earthquake on 6 June 2008. Before the 5 July 2008 earthquake, the fluctuation in the sunrise terminator time about the mean is observed to be 22 min 44 s.

The actual VLF data of some of the days during observation period has been presented in Fig. 4, wherein only 4 h data (from 3:00 to 7:00 hrs) has been plotted. The vertical arrow marks represent the sunrise terminator times. The shifting of terminator

Table 1—Place and magnitude of earthquakes with observed DLFT

Dates of earthquake	No. of day of the year	Magnitude of earthquakes (in Richter scale)	Observed DLFT (min)			Place of earthquake
			One day before earthquake	On the day of earthquake	One day after earthquake	
8 May 2008	129	4.1	31.117	33.633	61.083	Nepal - Tibet border region
12 May, 2008	133	7.5	39.750	38.533	38.317	China
29 May 2008	150	4.2	43.617	37.733	40.2	Darrang, Assam, India
6 June 2008	158	4.3	53.55	24.717	33.55	Gaya, Bihar, India
15 June 2008	167	4.5	48.983	45.367	26.267	Pithoragarh, Uttarakhand, India
19 June 2008	171	4.8	68.817	25.617	54.433	Nicobar Islands, India
27 June 2008	179	6.7, 5.8, 5.0	28.833	26.667	49.25	Andaman Islands, India
28 June 2008	180	5.4, 6.1, 5.5	26.667	49.25	32.017	Andaman Islands, India
29 June 2008	181	5.1, 5.2	49.25	32.017	35.867	Andaman Islands, India
5 July 2008	187	4.1	31.167	27.467	35.9	West Bengal, India
7 July 2008	189	5.0	35.9	30.167	39.633	Andaman Islands, India

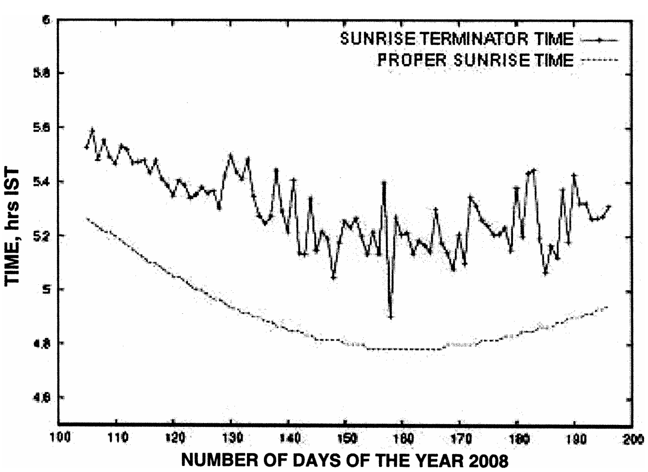

Fig. 3—Plot of sunrise terminator time (SRT) and proper sunrise time from 14 April to 14 July 2008. It shows the anomaly in SRT around seismically active days

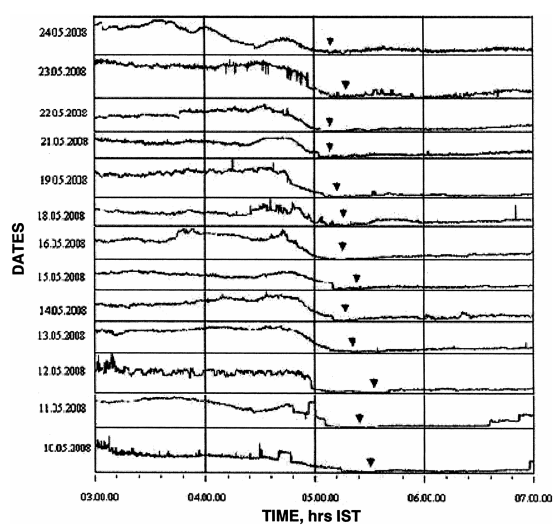

Fig. 4—Four-hour data around the sunrise terminator. Vertical arrow marks indicate the terminator times

times can be clearly seen from the shifted positions of the arrow marks.

Figure 5 shows the plot of DLFT versus day number of the year 2008. Mean DLFT is calculated excluding the data of those days on which there was an earthquake. The $(m + 2\sigma)$ and $(m - 2\sigma)$ lines are shown respectively above and below the mean DLFT line where m represents the mean DLFT and σ is the standard deviation which have been estimated based on the period of observation. The days of earthquakes are marked by '*' marks in Fig. 5. It is clearly seen that the D-layer formation time is fluctuating about the mean before and after seismically active days. In some cases the fluctuations in DLFT are very prominent where it is beyond $m \pm 2\sigma$ values. The observed values of DLFT on one day before, one day after and on the day of earthquake are shown in Table 1. From the table, the DLFT is seen to vary abnormally before and/or after an earthquake. It is, thus, clear that there is a correlation of seismic activity with the anomalous behavior of DLFT. But any clear relation between values of DLFT and magnitude of earthquakes could not be sought. This may be because of the fact that the depth of the epicenter and the distance of the place of occurrence from the GCP were not taken into consideration in the present study. No solar flares or any other physical events that may perturb VLF data occurred during present observation.

4 Conclusions

The fluctuations in sunrise terminator time around seismically active days are shown in Figs 3 and 4. It is known that due to seismic activities the radon gas concentration rises abnormally above the earthquake epicenter. This causes excess ionization of the ionosphere and the D-layer is lowered by about 5 km and as a consequence the sub-ionospheric VLF signals get modulated. The evidences of anomalies in D-layer formation time (DLFT) due to earthquakes have also been presented in Fig. 5. It has been found that fluctuations in DLFT are either very high or very low before, during and after the days of earthquakes ('*' marks in Fig. 5). These anomalies may be caused due to lithosphere-ionosphere coupling. The seismo-electric fields arising out of this coupling may either enhance or diminish the ionization level. The larger the degree of ionization, the shorter is the DLFT and vice versa. This effect when added to the normal effect of solar irradiation during sunrise produces the observed results. It was found that on some occasions DLFT is deviated by greater than twice the standard deviation about the mean. These phenomena can be used as precursors of earthquake. But the actual location, time or magnitude of a future earthquake cannot be predicted using this method. If such VLF monitoring is carried out in a network over a wide area covering the entire earthquake prone zone, then an earthquake can be predicted with accuracy.

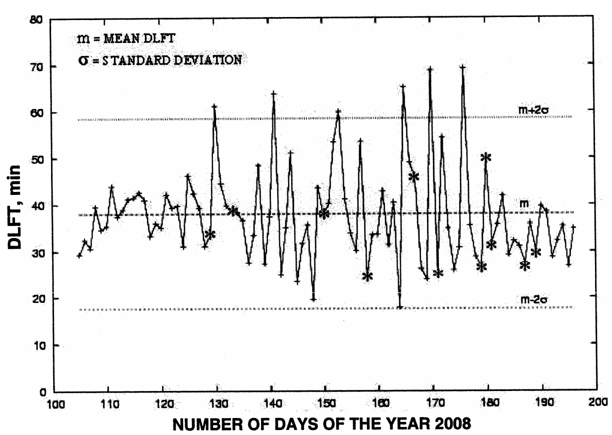

Fig. 5—Formation time of D-layer. The middle line represented by 'm' shows mean DLFT and the one above and below lines are respectively 'm+2σ' and 'm-2σ' lines; σ is the standard deviation; '*' marks represent the days of earthquakes

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