

## Extreme space-weather effect on D-region ionosphere in Indian low latitude region

K. Venkatesham and Rajesh Singh\*

K.S.K. Geomagnetic Research Laboratory, Indian Institute of Geomagnetism, Allahabad 221 505, India

**The present study delineates on the observations and modelling of low latitude D-region ionosphere perturbations caused by strongest solar flare (X6.9) of solar cycle 24. An extreme space weather event occurred on 9 August 2011. To understand the severity of X-class flare on ionosphere, a comparative study was made with a low intensity C-class flare of 6 August 2011. Both flares originated from the same sunspot AR#1263. Very low frequency (VLF) waves propagating in the Earth's ionosphere wave guide (EIWG) measured from VLF transmitter NWC (19.8 kHz) located in Australia, and recorded at Allahabad (India) were used. The recorded VLF amplitude and phase were modelled with long wavelength propagation capability code to understand solar flare-induced ionospheric variation. Modelling results revealed that the lower boundary of D-region ionosphere is lowered by 10 km during X-class and 1.0 km for C-class flare. This implies change in the properties of EIWG, and hence becomes important to observe our ionosphere on continuous basis for space weather events since ionosphere is the key medium of propagation for radio waves.**

**Keywords:** Low latitude, D-region ionosphere, solar flare, solar cycle 24, very low frequency waves.

SOLAR flares are recognized as extreme space weather phenomena, which is characterized by swift brightening of radiation within solar energetic areas of the sun and occur frequently during eleven years solar cycle peak years. During solar flares, a mammoth amount of energy is suddenly on the loose from the sun. This creates a burst of radiation which entirely covers the electromagnetic band, starting with radio waves to X-rays and  $\gamma$ -rays. This huge amount of energy released is categorized as per their brightness in X-ray spectrum in the wavelength  $\sim 1\text{--}8 \text{ \AA}$ . According to the intensity of radiation, solar flares are identified to be a source of plasma density disturbances in earth's ionosphere, but the region which is the disturbed most is the lowest part – the D-region<sup>1</sup>.

During the day, the primary source of ionization for the lowest region is largely Lyman- $\alpha$  (121.6 nm) emission of the solar origin, which to some extent ionizes  $\text{N}_2\text{O}$  composition, a neutral component in D-region, at 70 km altitude. When the sun is not active the X-ray flux from the sun is not enough to cause any noteworthy supplementary

ionization in the D-region ionosphere. But during solar flares, enhanced solar flux in the form of X-rays in the  $\sim 0.2\text{--}0.8 \text{ nm}$  wavelength range causes ionization of neutral and major  $\text{O}_2$  and  $\text{N}_2$  categories<sup>1,2</sup>. Hence extreme solar flares of high intensity modify the ionization level and hence change plasma density distribution in the ionospheric D-region. The plasma density changes caused by solar flares in the D-region have implications on the very low frequency (VLF, 3–30 kHz) waves propagation which essentially propagate in the naturally formed earth-ionosphere waveguide (EIWG) formed between the ionosphere lower boundary and ground surface<sup>3</sup>.

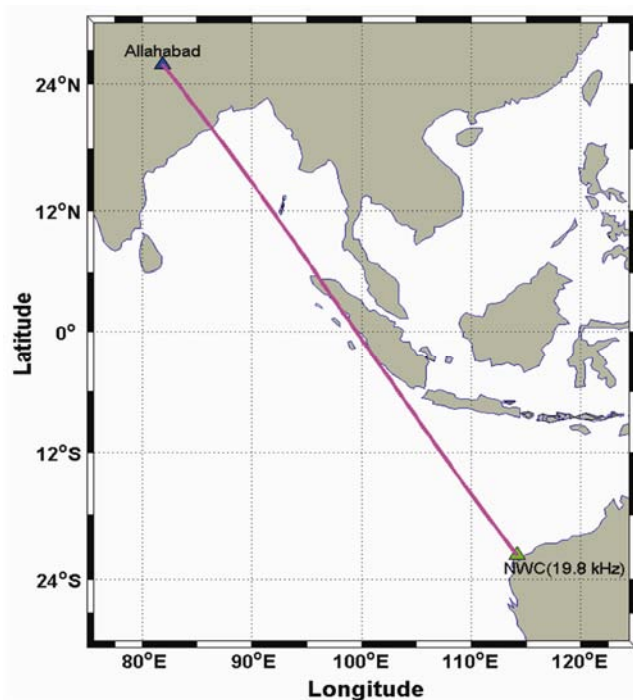
It is important to note that because of  $\sim 60\text{--}90 \text{ km}$  altitude range of day period D-region section of the ionosphere, it becomes difficult to study on diurnal or long-term period. The reason being that lower ionosphere is high for any balloon probe and in addition becomes inaccessible for satellites to allow any reasonable authentic measurements from above. Rockets and radars can be used, but these experiments are not designed for permanent monitoring. Studying D-region ionosphere with VLF waves is an economical experiment to continuously monitor the bottom part of the ionosphere for understanding dynamical processes of the region. VLF waves travel within the natural path created between the ground surface and the bottom boundary of ionosphere known as EIWG and hence any changes in the D-region ionosphere are reflected in VLF signal<sup>4,5</sup>.

Here we study the VLF observation and quantitatively model it to investigate 'strongest' solar-flare of solar cycle 24-induced perturbations in terms of density changes in lower ionosphere. X-class flare with intensity 6.9 and with its peak flux at  $\sim 08:05 \text{ UT}$  occurred on 9 August 2011. A weaker intensity C-class flare (4.1) which happened on 6 August 2011 at  $\sim 08:47 \text{ UT}$  was chosen to compare and understand the severity of X-class flare on D-region ionosphere in comparison to low intensity solar flare. A normal day with no flares (24 August 2011) was selected as the control day. The position of the flare on the disk of the sun is important in deciding its geo-effectiveness. Mostly the flares from sunspots located on the limb of solar disk are strong flares. In the present case, both X- and C-class flares considered for investigation originated from the same sunspot AR#1263 with solar disk location at  $18^\circ\text{N}$ ,  $80^\circ\text{W}$  on 9 August 2011. The details of solar flares were obtained from GOES satellites (<http://www.sec.noaa.gov>).

Location of the VLF recording site Allahabad (lat.  $25.75^\circ\text{N}$ , long.  $81.85^\circ\text{E}$ ) and NWC VLF transmitter (lat.  $21.8^\circ\text{S}$ , long.  $114.15^\circ\text{E}$ ) with its great circle path (GCP) is presented in Figure 1. For both X- and C-flares, time window of 2 h (07:30–09:30 UT) around their occurrence time was considered for analysis, which is the local Indian afternoon time (IST = UT + 5.5 h). Figure 2 a and b presents NWC (19.8 kHz) VLF signal amplitude variation (blue line) for both X-class (9 August 2011) and

\*For correspondence. (e-mail: rajeshsing03@gmail.com)

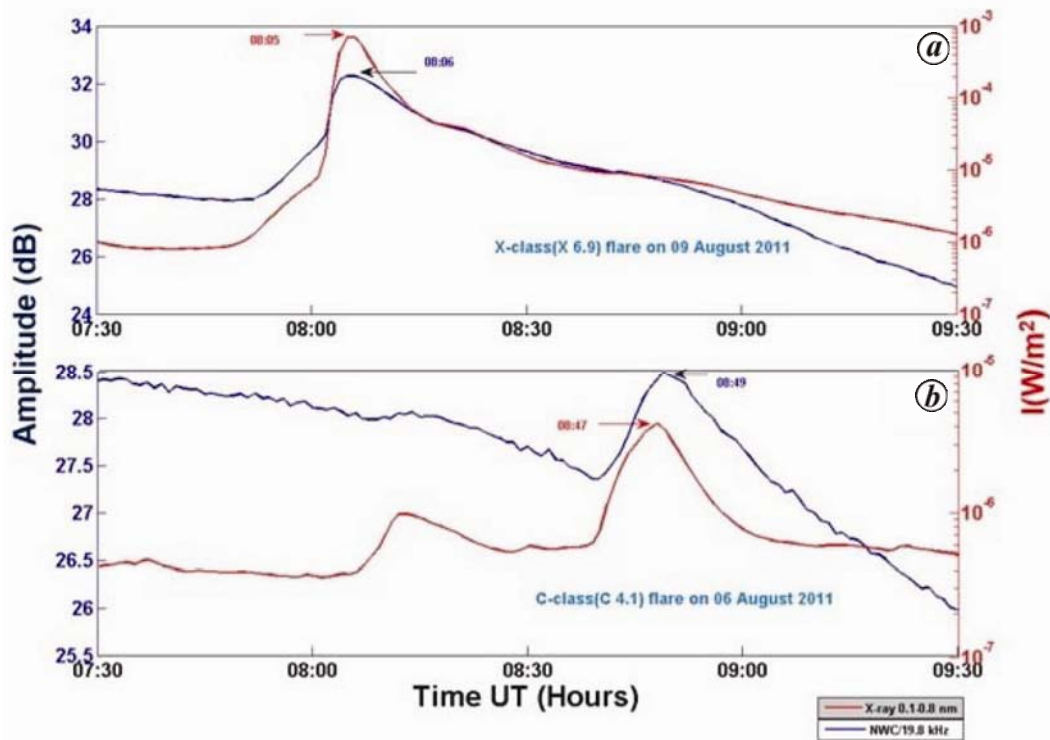
C-class (6 August 2011) flares with corresponding X-ray flux (red line) from GOES satellite observations. With propagation delay<sup>1</sup> ( $\Delta t$ ) to earth by  $\sim 1$  min the peak in VLF amplitude was observed at  $\sim 08:06$  UT (Figure 2 a). When compared to control day (24 August 2011) the amplitude enhancement was found to be of the order of  $\sim 4.56$  dB. For C-class flare with a delay of  $\sim 2$  min, the peak in VLF amplitude was noticed at  $\sim 08:49$  UT (Figure 2 b) and with amplitude enhancement of only  $\sim 0.89$  dB. During solar flare enhancements the observed VLF signal amplitude is attributed to extra ionization or plasma concentration induced in the D-region. The additional induced ionization results in sharpening of EIWG upper boundary and this in turn lowers the boundary of the ionosphere by more than a few hundred meters<sup>6</sup>. When VLF signal propagates in such a sharpened EIWG, due to multiple mirror reflection within it, consequences in the signal amplitude increase. The resulting amplitude changes clearly depend on the size of the flare<sup>7</sup>. A relation between propagation delay ( $\Delta t$ ) and change in ionospheric plasma density was given by Mitra<sup>1</sup>, which for the first time made researchers realize that propagation delay ( $\Delta t$ ) is inversely associated with change in plasma density.  $\Delta t$  is lower for higher plasma density, i.e. ionospheric change reply is quicker when plasma density is high. Depending on the intensity of X-class flares, D-region responds faster, resulting in minimum  $\Delta t$  value. In the present case  $\Delta t$  for X-class flares is  $\sim 1$  min and C-class flares is  $\sim 2$  min.



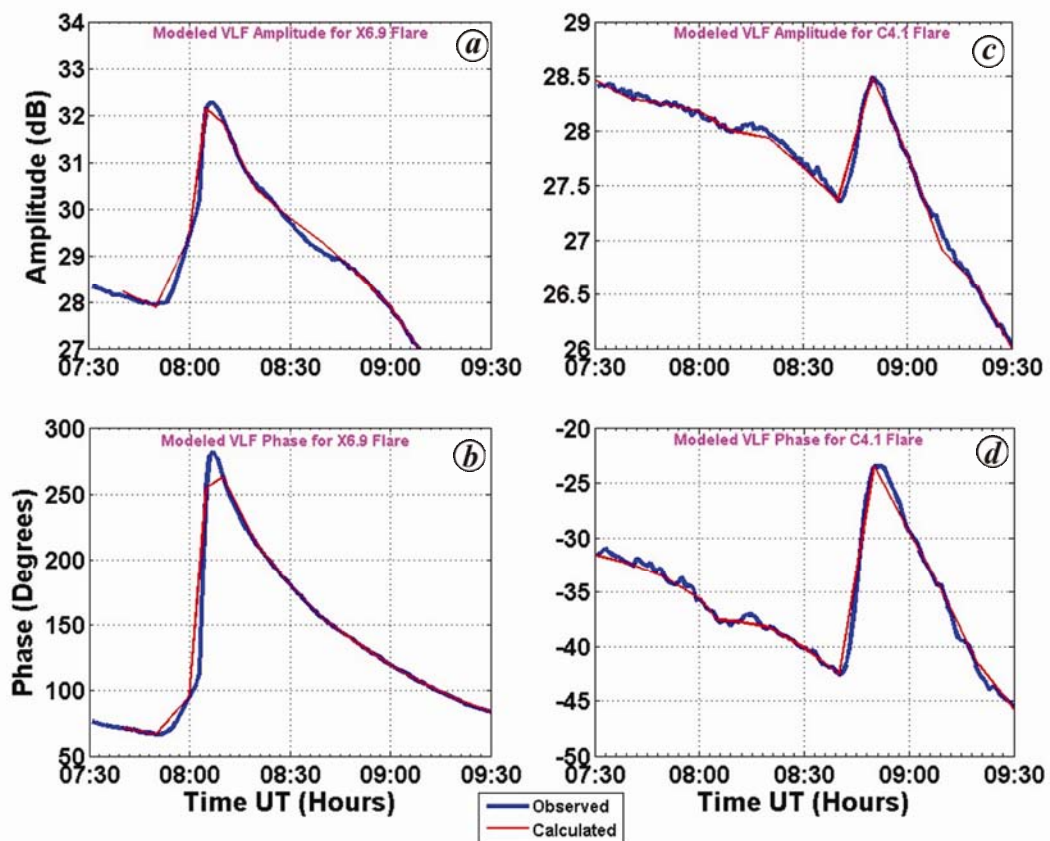
**Figure 1.** VLF receiver station and NWC transmitter. Green triangle indicates the location of NWC (19.8 kHz) VLF transmitter, blue triangle indicates the VLF receiver station and the line connecting (magenta) is great circle path (GCP) between two sites.

Further in order to resolve quantitatively the lower ionosphere electron concentration changes linked to X-class and C-class flares, the observed VLF signal variation is modelled by long-wavelength propagation capability (LWPC) model (V2.1)<sup>8</sup> for Wait's model of lower ionosphere. The Wait's ionosphere is characterized by two variables: the sharpness  $\beta$  ( $\text{km}^{-1}$ ) and reflection height  $H'$  ( $\text{km}$ )<sup>9</sup>. Figure 3 a and b presents the observation and modelling of NWC amplitude and phase for 9 August 2011, X-class solar flares. Figure 3 c and d shows the same for 6 August 2011, C-class solar flares. LWPC model was run every 15 min from 07:30–09:30 UT for both X- and C-class flares. LWPC calculates changes in Wait's ionospheric parameters,  $H'$  and  $\beta$ . The LWPC modelled output  $H'$  and  $\beta$  was selected for the finest match between the LWPC modelled and recorded amplitude and phase. When compared to unperturbed control daytime ionosphere (24 August 2011) LWPC gave  $\beta = \sim 0.30 \text{ km}^{-1}$  and  $H' = \sim 74.0 \text{ km}$ . The modelled values for C-class flares were found to be  $H' = \sim 73.0 \text{ km}$  and  $\beta = \sim 0.32 \text{ km}^{-1}$ . This represents decline in  $H'$  by 1 km, and enhancement in  $\beta$  as  $0.02 \text{ km}^{-1}$ . For X-class flares of 9 August 2011 the values obtained are  $H' = \sim 64.0 \text{ km}$  and  $\beta = \sim 0.39 \text{ km}^{-1}$ . This decreases  $H'$  by 10 km, and increases in  $\beta$  by  $0.09 \text{ km}^{-1}$ . Hence for X-class flares boundary of ionosphere was lowered by  $\sim 10 \text{ km}$  and for C-class by  $\sim 1.0 \text{ km}$  only.

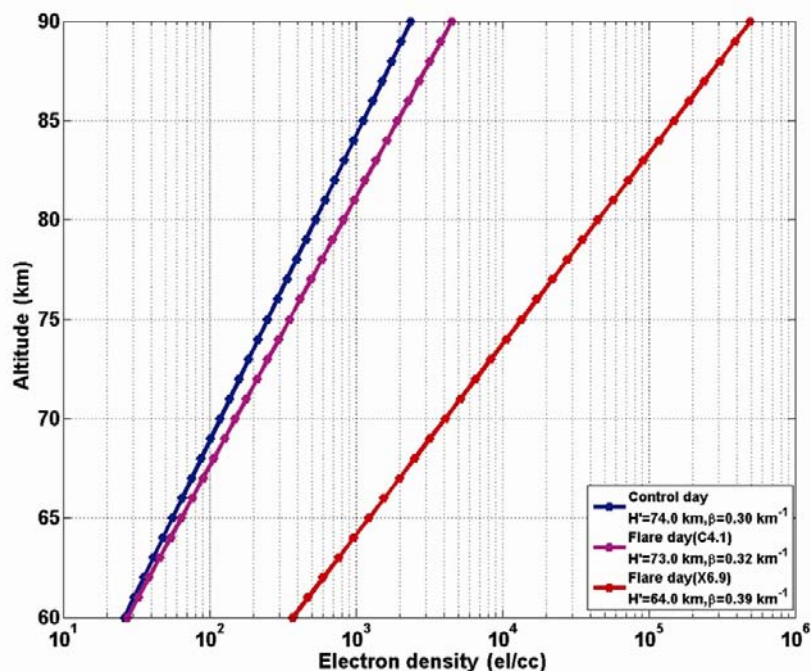
The lowering of ionosphere can be understood in terms of increase in D-region plasma density. The D-region electron density height profiles  $N_e(h)$  in  $\text{cm}^{-3}$  applicable up to  $\sim 100 \text{ km}$  height for our recording site is drawn with Wait's profile following  $N_e(Z) = 1.43 \times 10^7 \exp(-0.15H') \times \exp[(\beta - 0.15)(Z - H')]$  (ref. 9). Figure 4 shows electron density  $N_e(h)$  profile obtained in the altitude range of 60–90 km for the control day of 24 August 2011 (blue line) and X-class (red line) and C-class (magenta) solar flares. The electron density is clearly larger for extreme space weather events of X-class solar flares, when compared to C-class solar flares and the control day. Low latitude results when compared to mid-latitude observations are important to note. In a mid-latitude study, McRae and Thomson<sup>7</sup> showed that for X3.0 flare, reduction in reflection height ( $H'$ ) is within  $\sim 71$ – $59 \text{ km}$  ( $\Delta H' = \sim 12 \text{ km}$ ) and increase in sharpness factor ( $\beta$ ) is in the range  $\sim 0.39$ – $0.52 \text{ km}^{-1}$  ( $\Delta\beta = \sim 0.13 \text{ km}^{-1}$ ). For other X5.0-class flares it was found that  $H'$  decreased starting with  $\sim 71$ – $58 \text{ km}$  ( $\Delta H' = 13 \text{ km}$ ) along with increase in  $\beta$  starting  $\sim 0.39$ – $0.52 \text{ km}^{-1}$  ( $\Delta\beta = \sim 0.13 \text{ km}^{-1}$ ). In one of the low latitude studies in the Pacific region by Kumar *et al.*<sup>10</sup> for a X1.5 solar flare it was found that the ionosphere is lowered by  $\Delta H' = 11.1 \text{ km}$  and  $9.4 \text{ km}$  on two different VLF propagation paths. In our result for low latitude Indian region for a solar flare of higher intensity (X6.9) it was found that the ionosphere is lowered by  $\Delta H' = 10 \text{ km}$ , which is lower when compared to low and mid-latitude results on other sectors of the globe as mentioned above.



**Figure 2.** Variation of X-ray flux (red) detected from GOES satellite and NWC VLF transmitter signal amplitude (blue). *a*, 9 August 2011, X-class solar flare; *b*, 6 August 2011, C-class solar flare.



**Figure 3.** LWPC modelled VLF amplitude and phase for 9 August 2011, X-class solar flare (*a*, *b*) and 6 August 2011, C-class solar flare (*c*, *d*).



**Figure 4.** Comparison of electron density  $N_e(h)$  profile obtained in the altitude range 60–90 km both for geomagnetically quiet day of 24 August 2011 (blue line) with C-class (magenta) and X-class (red line) solar flares.

Solar flares are one of the important components of extreme space weather events which greatly influence the earth's ionosphere and hence radio wave propagation in upper space environment. To summarize the observations, it is important to note that a solar flare occurring during the afternoon is very important. The strongest solar flare of solar cycle 24 on 9 August 2011 with intensity X6.9 happened to occur during mid-afternoon and resulted in the lowering of ionosphere boundary by 10 km. It would be of scientific importance when all X-class flares along with minor class flares of solar cycle 24 are analysed in three different groups as per their time of occurrence, i.e. morning, afternoon and evening. With continuous VLF data from 2007 onwards at the Indian Institute of Geomagnetism, it proposed to consider all C-, M- and X-class solar flares of 24 solar cycle and undertake a comprehensive analysis to understand the effects of extreme space weather events on the ionosphere. This would be the first study to cover a complete solar cycle of 11 years in Indian low latitude region.

- Mitra, A. P., *Ionospheric Effects of Solar Flares*, D. Reidel, Dordrecht-Holland, 1974.
- Hargreaves, J. K., *The Solar-Terrestrial Environment*, Cambridge University Press, New York, 2003.
- Thomson, N. R., Rodger, C. J. and Clilverd, M. A., Large solar flares and their ionospheric D-region enhancements. *J. Geophys. Res.*, 2005; doi:10.1029/2005JA011008.
- Maurya, A. K. *et al.*, Morphological features of tweeks and nighttime D region ionosphere at tweek reflection height from the

observations in the low-latitude Indian sector. *J. Geophys. Res.*, 2012; doi:10.1029/2011JA016976.

- Rajesh, S. *et al.*, Very low latitude ( $L = 1.08$ ) whistlers. *J. Geophys. Res.*, 2012; doi:10.1029/2012GL054122.
- Thomson, N. R. and Clilverd, M. A., Solar flare induced ionospheric D-region enhancements from VLF amplitude observations. *J. Atmos. Solar Terr. Phys.*, 2001, **63**(7), 1729–1737.
- McRae, W. M. and Thomson, N. R., Solar flare induced ionospheric D-region enhancement from VLF phase and amplitude observations. *J. Atmos. Solar Terr. Phys.*, 2004, **66**, 77–87.
- Ferguson, J. A. and Snyder, F. P., Computer programs for assessment of long wavelength radio communications, version 1.0: Full FORTRAN code user's guide. Nav. Ocean Syst. Cent., Tech. Doc. 1773, DTIC AD-B144 839, Def. Tech. Inf. Cent, Alexandria, Va, 1990.
- Wait, J. R. and Spies, K. P., Characteristics of the earth-ionosphere waveguide for VLF radio waves. Tech. Note 300, Natl. Bur. of Stand., Boulder, Colorado, 164.
- Kumar, S. *et al.*, Response of the low-latitude D region ionosphere to extreme space weather event of 14–16 December 2006. *J. Geophys. Res.*, 2015; doi:10.1002/2014JA020751.

**ACKNOWLEDGEMENTS.** We thank the Director, Indian Institute of Geomagnetism (IIG) for support and encouragement to carry out the work. Solar flares X-ray flux data were taken from Geostationary Operational Environmental Satellite (GOES) (<http://www.sec.noaa.gov>). The NWC (19.8 kHz) VLF data was from the IIG operated VLF station at Allahabad.

Received 21 September 2016; revised accepted 30 November 2017

doi: 10.18520/cs/v114/i09/1923-1926