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ORIGINAL ARTICLE

Solar flare induced D-region ionospheric perturbations evaluated from VLF measurements

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Abstract The results of very low frequency (VLF) wave amplitude measurements carried out at the low latitude station Varanasi (geom. lat. 14°55′N, long. 154°E), India during solar flares are presented for the first time. The VLF waves (19.8 kHz) transmitted from the NWC-transmitter, Australia propagated in the Earth-ionosphere waveguide to long distances and were recorded at Varanasi. Data are analyzed and the reflection height H' and the sharpness factor β are evaluated. It is found that the reflection height decreases whereas sharpness factor increases with the increase of solar flare power. The H' is found to be higher and β smaller at low latitudes than the corresponding values at mid and high latitudes. The sunspot numbers were low during the considered period 2011–2012, being the rising phase of solar cycle 24 and as a result cosmic rays may impact the D-region ionosphere. The increased ionization from the flare lowers the effective reflecting height, H', of the D-region roughly in proportion to the logarithm of the X-ray flare intensity from a typical mid-day unperturbed value of about 71–72 km down to about 65 km for an X class flare. The sharpness (β) of the lower edge of the D-region is also significantly increased by the flare but reaches a clear saturation value of about 0.48 km^{-1} for flares of magnitude greater than about X1 class.

Keywords Sun: flares, X-rays · Waves: VLF · Ionospheric perturbations

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1 Introduction

The neutral atmosphere in the lower D-region (∼50–70 km) is ionized mainly by solar EUV radiation and galactic cosmic rays. Although, the down going solar EUV radiation is increasingly absorbed by the increasing atmospheric density, but the available free electron density become very small due to high electron attachment and recombination rates. The partially ionized lower D-region forms the upper boundary of the Earth-ionosphere waveguide, while the oceans and ground form the lower boundary. Usually these boundaries are stable and allow VLF waves (∼3–30 kHz) propagation with little or no perturbation. Occasionally solar flares (Mitra 1974; Thomson et al. 2004), geomagnetic storms (Peter et al. 2006), solar proton events (Clilverd et al. 2006), γ-ray bursts (Tanaka et al. 2010), solar eclipse (Klobuchar and Whitney 1965; Singh et al. 2012), lightning discharges (Rodger 1999), particle precipitations due to whistler mode wave particle interaction (Inan et al. 2010) and earthquakes (Hayakawa et al. 1996) could produce additional ionization in the lower D-region and perturb the upper boundary of the Earth-ionosphere waveguide. As a result the amplitude and phase of the VLF waves propagating through the Earth-ionosphere waveguide also get perturbed (Pant 1993; Rodger 1999). Observations of these waves are used as one of the best probes available for characterizing the height and sharpness of the lower D-region (Thomson 2010; Thomson et al. 2011). Amongst the other techniques, rockets yields good results but they are expensive and transient and practically it is not possible to use the technique for diurnal, seasonal and latitudinal studies. Other techniques such as incoherent scatter radar, balloons, satellites, etc have limitations due to low altitudes and large air densities (Inan et al. 2010).

The solar X-ray flux under normal condition is too small to be a significant source for ionization, however, when a solar flare occurs there is an abrupt enhancement in the X-ray flux (∼0.1–0.2 nm) which could ionize the dominant particles N_2 and O_2 and lowers the D-region effective height. Although the general effects of solar flares on the D-region of the ionosphere have been reported on many times in the past (Mitra 1974; McRae and Thomson 2004 and references therein), only recently a quantitative study of the relationship between the size of the flare and its consequent increase in the electron density in the D-region has been made (Le et al. 2013). Thomson (2010) from the analysis of short VLF path measurements during flare events showed that mid-day tropical/equatorial region can be well modeled by virtual reflection height $(H') = 70.5 \pm 0.5$ km and the sharpness of the lower edge $(\beta) = 0.47 \pm 0.03$ km^{-1} where H' and β are traditional Wait parameters (Wait 1959; Wait and Spies 1964). The long path measurement of Wait parameters for NWC-Seattle (∼ 14 Mm) path during the solar flare event matches well with the values derived from short path measurements (Thomson et al. 2011). If the observation site is at higher latitudes, the value of β would be relatively smaller due to much higher cosmic ray fluxes at higher latitudes. Pacini and Raulin (2006) showed that during solar flares only soft X-ray photons can penetrate down to 70 km and lower altitude which may produce significant enhancement in ionization resulting in variations of one or both the Wait parameters.

It is known that some of the X-ray solar flares are accompanied with Lyman-α radiation excesses while others are not. The Lyman-α radiation usually can penetrate down to the 70 to 75 km altitude, where it becomes the main agent in the direct ionization of NO (Kockarts 2002) and is responsible for the formation of the D-region. It is pertinent to evaluate the impact of the Lyman-α excesses associated with the X-ray solar flare. Recently, Raulin et al. (2013), analyzing changes of the VLF wave phase during moderate to medium size solar flares produced by the Lyman-α flare excesses showed that the produced phase changes were about 20 times below the sensitivity of the present VLF measurements. Response of D-region ionosphere to the solar flare is stronger during the solar minimum than during the solar maximum i.e. quiescent ionospheric reference height is higher for the solar minimum condition than that for the solar maximum (Pacini and Raulin 2006). Still the detailed study of the effect of solar flares on D-region of the ionosphere remains to be fully identified, particularly those observed at low latitudes. In view of this aim, the present study has been initiated to quantify the solar flare induced D-region ionospheric perturbations which is evaluated from VLF measurements observed at low latitude. The observations of perturbations of ionospheric D-region during intense solar flares at low latitude Indian ground station Varanasi also become interesting because the station is located near the edge of equatorial anomaly region. In contrast most of the reported studies are from either mid-latitude or from high latitude stations (McRae and Thomson 2004; Thomson et al. 2004, 2011).

The solar flare-induced amplitude perturbations of VLF waves transmitted from the NWC, Australia (geog. lat. 21°45′S geog. long. 144°10′E) and received at Varanasi are analyzed and the results are presented. Most of the VLF paths lies over oceans. At Varanasi, VLF signal from the NWC transmitter is continuously recoded from 2011. During the last two years (2011–2012), 32 events of solar flares monitored by GOES satellites are identified. Corresponding to these events, VLF wave amplitude enhancements are measured and analysis is carried out. Section 2 describes briefly experimental set up and analysis technique. Results and discussions are given in Sect. 3. The great circle path from NWC, Australia (transmitting station) to the receiving station, Varanasi, India is 6230 km with the middle part of the Earth-ionosphere waveguide over Atlantic Ocean, making the path long daylight and sea dominant. Results are summarized in Sect. 4.

2 VLF measurements and analysis

The AWESOME ELF/VLF receiver developed by Solar Center of the Stanford University, USA (Cohen et al. 2009) has been installed at the campus of Banaras Hindu University (geog. lat. 25°15′20″N, long. 82°59′21″E). The receiver is capable of recording two types of data: broadband data (300 Hz to 47.5 kHz) and narrowband data. The recording system consists of two orthogonal crossed loop antennas with 10 × 10 m base aligned in North–South (N-S) and the East–West (E-W) magnetic planes, matched pre-amplifier and line receiver. The pre-amplifier is kept near the receiving antenna to reduce the attenuation of the received signals. The amplified signal is then fed to the line receiver kept in the recording room, connected by a ∼100 m long cable. Time synchronization is achieved by the GPS clock connected with the line receiver. Recorded VLF data are stored in a recording PC at 100 kHz, 16-bit sampling rate and 10 micro-seconds time resolution. These sampled data are analyzed by codes developed in MATLAB (Cohen et al. 2009) and modified by us to suit our data recorded at the low latitude station Varanasi.

The solar flare produced additional ionization in the D-region perturbs (usually enhancements) the amplitude and phase of the VLF signals transmitted from the phase stable transmitters. The observed amplitude changes are modeled using the Long Wave Propagation Capability (LWPC) waveguide codes to find the values of H' and β which match the measurements (Thomson et al. 2011). The amplitude change $\Delta A = A_{\max} - A_{\mathrm{background}}$, where $A_{\max}$ is the value of peak amplitude reached during the particular solar flare and $A_{\text{background}}$ is the monthly mean value of amplitude at the time of peak amplitude perturbation for quiet days (Todoroki et al. 2007). The perturbation in phase for all the solar flares could not be determined as it was unstable during most of the flares. Solar flare-induced perturbations in all cases showed an enhancement in the amplitude and an increase in the phase under stable phase conditions.

The unperturbed values of H' and β in the absence of solar flare are quite stable and well known from VLF amplitude observations, (McRae and Thomson 2000; Thomson and Clilverd 2000). Thomson (2010) based on the day-time tropical/equatorial D-region ionosphere measurement from VLF phase and amplitude, showed that ionosphere can be well modeled by $H' = 70.5 \pm 0.5$ km and $\beta = 0.47 \pm 0.03\ \text{km}^{-1}$. For the present study, we have considered $H' = 71$ km and $\beta = 0.43\ \text{km}^{-1}$ for the unperturbed ionosphere (Thomson 1993). Using these values as normal base level, the values of H' and β during solar flares can generally be found uniquely from the observed VLF amplitude observed during the flare and using exponential electron density profile of the D-region ionosphere, which is given by Thomson (1993) as:

$$\mathrm{Ne}(h) = 1.43 \times 10^{13} \cdot \exp(-0.15H') \times \exp[(\beta - 0.15) \cdot (h - H')]\ \mathrm{m}^{-3} \tag{1}$$

where H' is the D-region virtual reflection height in kilometers and β is Wait inverse scale height parameter in km^{-1}.

3 Results and discussion

VLF transmitters around the world are used for navigation purposes and they have very good phase and amplitude stability. The Australian NWC transmitter operating at 19.8 kHz goes-off air once a week for 6–8 hours maintenance. On return to air, the phase is normally stable but the value of phase relative to GPS may or may not be persevered. Even some times there may be gradual phase drift or random phase jumps. Therefore, while doing phase analysis theses points have to be taken into consideration. However there are no such problems with the amplitudes. In the present work, we have considered solar flares with the magnitudes greater than M1 class. M1 means the X-ray flux of $1.0 \times 10^{-5}\ \mathrm{W\,m^{-2}}$. The analyzed solar flares are listed in Table 1. The date, peak occurrence time, the change in VLF amplitude and derived values of H' and β are also given in the table. The solar X-ray fluxes are measured sequentially by SOLRAID satellite and then by GOES satellites from 1975. In this study, we used one minute averaged X-ray flux data in the XL band observed by GOES satellites, taken from the NOAA's National Geophysical Data Center (http://www.ngdc.noaa.gov/).

Figure 1a shows the temporal variation of the VLF waves amplitude recorded at Varanasi and the X-ray flux of class X1 solar flare observed from GOES 15 satellite on 05 March 2012. We observe almost identical variation of wave amplitude and X-ray flux with a maximum around 0409 UT. The value of ΔA evaluated from the VLF measurement is found to be 3.40 dB. Using this value of ΔA, the Wait parameter H' and β is obtained to be 67.26 km and $0.464\ \text{km}^{-1}$ respectively. These values are used to determine the height profile of the electron density during the solar flare period. To compare it with the unperturbed electron density, computations have also been made with $H' = 71$ km and $\beta = 0.43\ \text{km}^{-1}$ (McRae and Thomson 2004) and the results are shown in Fig. 1b. The electron density during the solar flare increases in the D-region. Figure 1b shows the height profile of electron density on logarithmic scale and the percentage change in the electron density on linear scale is shown in Fig. 1c. Near the reference height of 71 km, the increase in electron density is 475 %.

Figure 2a shows the temporal evolution of the solar flare events of 9 March 2012 consisting of two solar flares of class C4 and M6 and corresponding changes in the VLF amplitude. The C4 flare had maximum intensity at 0200 UT. At the end of C4 flare, M6 flare begins and becomes maximum at 0353 UT. During the flare, the VLF amplitude variation is proportional to the X-ray flux intensity. The observed ΔA values were 0.96 dB and 2.00 dB respectively for class C4 and M6 solar flares. Using the observed change in amplitude the values of H' and β are obtained as 69.944 km and $0.4396\ \text{km}^{-1}$ for the C4 class solar flare; 68.80 km and 0.45 km^{-1} for the M6 class solar flare. Using these values, height profile of electron density in the D-region during the class C4 and M6 solar flares and in the absence of solar flares are derived. From these values the percentage change from the unperturbed state is determined. The height profile of electron density and percentage change in the electron density are shown in Fig. 2b and 2c respectively. The percentage increase in the electron density at the reference height of 71 km comes out to be 53 % and 110 % for C4 and M6 class of flares respectively. We can see in Fig. 2a, as for M6 class flare the peak of the LF transmitter signal amplitude precedes the peak of the X-ray flux. This may be due to successive flare and elongated time for peak occurrence after abrupt onset of flare. Due to first abrupt onset of flare electron density of D-region increases and hence the sharpness factor and VLF amplitude. There occur a successive flare before the occurrence of the peak and peak flux time is shifted (elongated). The successive enhancement in X-ray flux intensity does not have much effect on the D-region sharpness profile hence the VLF wave get peak preceding the flare peak.

Table 1 The details of some of the strong solar flares occurred during 2011 & 2012

DATE	Flare class	Peak time (UT)	ΔA (dB)	H' (km)	β (km^{-1})
12 March 2011	M1	04:43	1.63	69.207	0.4463
4 August 2011	M9	03:57	2.46	68.294	0.4546
	C5	08:02	0.68	70.252	0.4368
9 August 2011	M2	03:54	2.18	68.602	0.4518
	X6	08:05	4.83	65.687	0.4783
2 October 2011	M3	00:50	2.08	68.712	0.4508
22 October 2011	M3	03:50	2.10	68.690	0.4510
17 Jan 2012	M1	04:53	2.07	68.770	0.4502
23 Jan 2012	M1	03:15	1.88	68.934	0.4487
	M8	03:59	2.26	68.507	0.4526
5 March 2012	X1	04:09	3.40	67.260	0.4640
9 March 2012	C4	02:00	0.96	69.944	0.4396
	M6	03:53	2.00	68.800	0.4500
15 March 2012	M1	07:52	1.13	69.757	0.4413
6 May 2012	M1	01:18	0.33	70.637	0.4333
	C3	04:36	1.13	69.757	0.4413
10 May 2012	M5	04:18	2.55	68.195	0.4555
	C8	05:22	0.68	70.252	0.4368
29 June 2012	C6	01:25	0.42	70.538	0.4342
	M2	09:20	1.36	69.504	0.4436
4 July 2012	M2	04:37	1.32	69.548	0.4432
	M5	09:55	2.03	68.767	0.4503
8 July 2012	M1	05:46	1.28	69.592	0.4428
	M1	09:53	0.79	70.131	0.4379
10 July 2012	M1	05:14	1.28	69.592	0.4428
	M2	06:27	1.70	69.130	0.4470
18 Aug 2012	M5	01:02	2.88	67.832	0.4588
	M1	03:23	1.58	69.262	0.4458
	C6	06:18	1.01	69.889	0.4401
6 Sept 2012	M1	04:13	1.66	69.174	0.4466
08 Nov 2012	M1	02:23	2.27	68.503	0.4527
21 Nov 2012	M1	06:56	1.34	69.526	0.4434

We have analyzed another interesting event when two intense solar flare of the class M2 and M5 occurred on 4 July 2012. The flare M2 has maximum flux at 0437 UT and M5 has its maximum at 0955 UT. The variations of X-ray flux (in logarithmic scale) and corresponding amplitude variation in VLF signal during the solar flare are shown in Fig. 3a. The ΔA values were 1.32 dB and 2.03 dB, for the flare class of M2 and M5 fluxes respectively. From the amplitude perturbations β and H' are computed which are found to be $\beta = 0.4432$ km^{-1} and $H' = 69.548$ km for M2 and $\beta = 0.4503$ km^{-1} and $H' = 68.767$ km for M5 class flares. The height profile of electron density and percentage change from the unperturbed stage for M2 and M5 class flares are shown in Fig. 3b and 3c. The percentage change at the reference height of 71 km comes out to be 90 % and 175 % respectively. Thus it is observed that for stronger class of flares the increase in electron density is more.

Figure 4a shows the temporal variation of X-ray flux and VLF amplitude for the three consecutive solar flares of class M5, M1 and C6 observed on 18 August 2012. The flare M5 becomes maximum at 0102 UT after that M1 class flare begins and maximizes at 0323 UT. Almost after two hours of M1 class, class C6 solar flare occurred. In the same figure, we have also shown the temporal variation of the monthly mean value (background amplitude) during this time excluding the disturbed days. It was noted that the amplitude of VLF wave before the start of solar flare and after the occurrence of all the three flares, matched well. However just after the first solar flare, the amplitude becomes slightly lower than the average unperturbed value. The change in VLF sig-

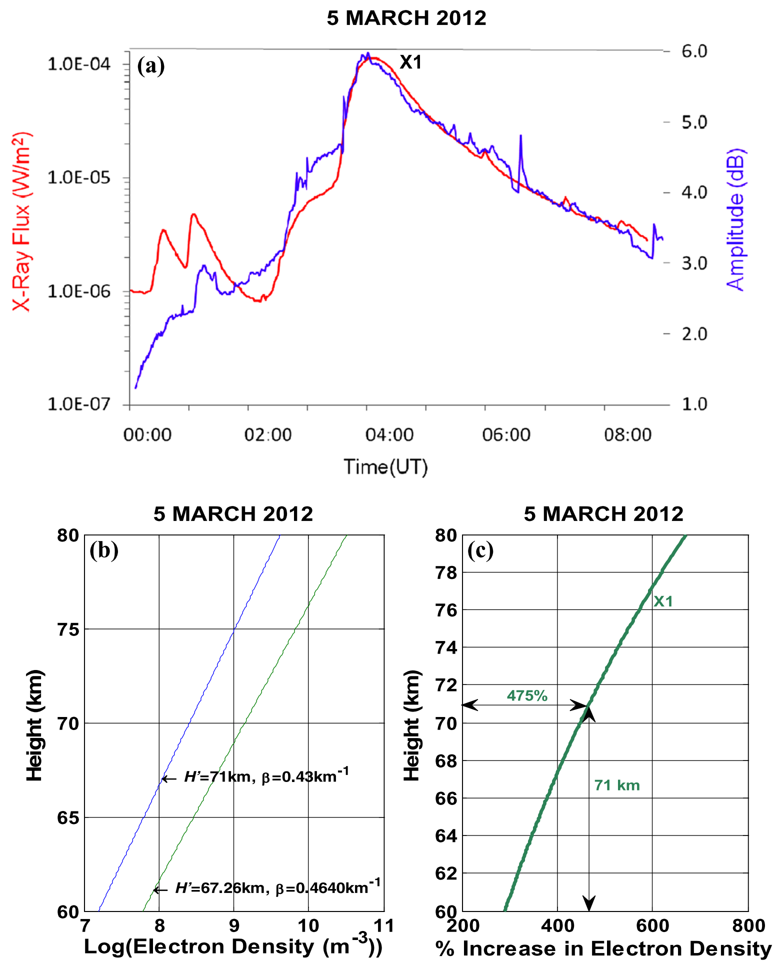

Fig. 1 (**a**) Temporal variation of X-Ray flux and VLF signal (19.8 kHz) received at BHU, Varanasi during solar flare event of 5 March 2012. (**b**) The height profile of electron density (logarithmic scale), and (**c**) percentage increase in electron density (linear scale) corresponding to the event of (**a**)

nal amplitude follows the X-ray flux variation and the maximum change in amplitude corresponding to M5, M1, and C6 is 2.88 dB, 1.58 dB and 1.01 dB respectively. The changes in amplitude is used to determine H' and β, which comes out to be 67.832 km, 0.458 km^{-1} for M5, 69.267 km, 0.4488 km^{-1} for M1, and 69.889 km, 0.4401 $km^{-1}$for C6 solar flare respectively. The height profile of enhanced electron density and percentage change in it are given in Figs. 4b and 4c respectively. The percentage change at 71 km comes out to be 320 %, 110 % and 50 % respectively for M5, M1 and C6 class solar flares.

Thomson et al. (2005) computed D-region electron density before and during the great solar flare X45 of 4 November 2003 and showed height profile. The percentage change in that case at the altitude of 71 km comes out be 830 %. They have also shown electron density variation for X6 flare and electron density measured from incoherent scatter radar during an X6 flare. The percentage change for X6 flare comes out to be 530 %. The incoherent scatter radar measurement at Arecibo (Zinn et al. 1990) showed that VLF measurement above 62 km becomes insensitive. Therefore, it is suggested that at low latitudes in addition to VLF measurements, Incoherent scatter radar or any other technique should also be used to probe the D-region during solar flares or other space weather events.

During 2011 and 2012, we have identified 24 solar flares for which VLF amplitude measurements were available. These solar flares have been analyzed and H' and β are computed. The variation of β and H' with the solar flare power are shown in Figs. 5a, b. β increases with the X-ray flux, whereas H' shows a decrease with it. This higher value of H' and smaller β correspond to small value of the D-region electron density. That is, the increased amount of the electron density at low latitudes is less than that at mid and high latitudes during solar flares. β initially slowly increases with the flare power and the trend (extrapolated) as shown by green line shows an increase at higher flare power (Fig. 5a). In the same figure we have also shown the results of Thomson et al. (2005) which also represents the three very large solar flares: the X20 of 02 April 01 (shown by blue circle), the X10 of 29 Oct 03 (shown by purple circle) and the great solar flare X45 of 04 Nov 03 (shown by red circle). This shows that at high flare powers, β does not fully flatten off for flare sizes $>$ X5 as had previously been indicated (McRae and Thomson 2004), but continues to rise sharply. Our extrapolated curve shows slightly lower values

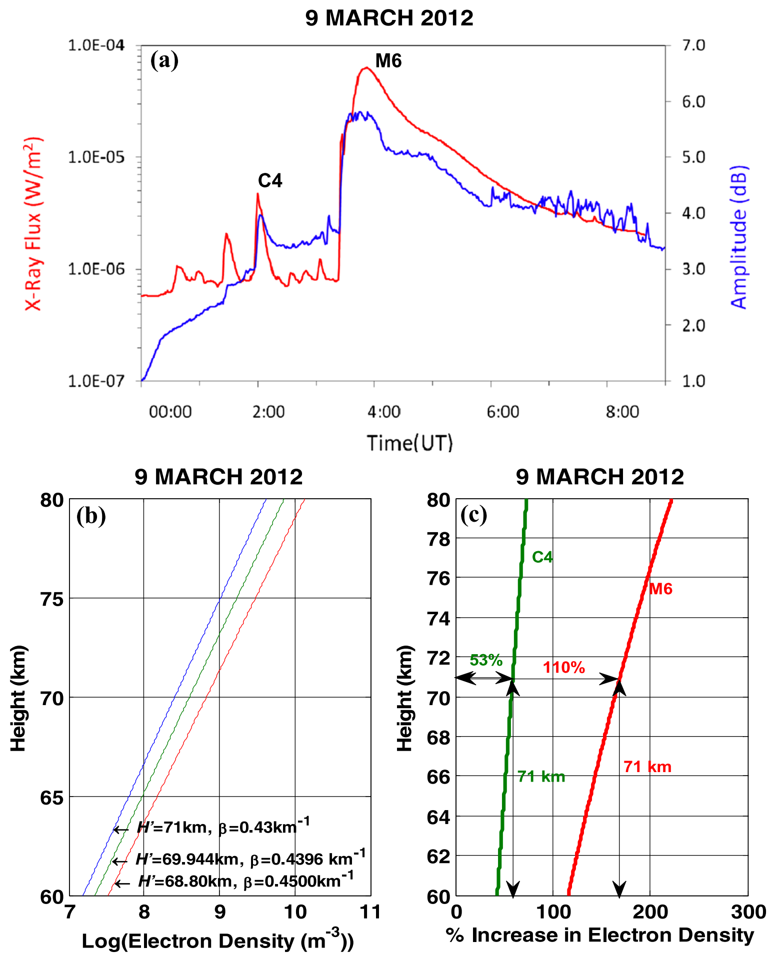

Fig. 2 (**a**) Variation of X-Ray flux and VLF signal amplitude of NWC, as received at BHU, Varanasi during solar flare event of 9 March 2012. (**b**) The logarithmic electron density and (**c**) percentage increase in it with altitude during solar flare event of 9 March 2012

but represents the trend. The curve is represented by a cubic polynomial. The results of Thomson et al. (2005) are also represented by a cubic polynomial. The constants of the polynomial in our case differ from that of Thomson et al. (2005). Our results broadly are in agreement with those of Thomson et al. (2005) and McRae and Thomson (2004). The amplitude changes are typically more dependent on β than H' for long path (Thomson et al. 2005). This contributes, at least partly, to both the spread of the β values, on the one hand, and to the coherence of the H' values, on the other. In the computation of electron density profile, the values of H' and β during a flare were considered constant along the path of VLF wave propagation. This equivalently means that the effects of the flare are independent of solar zenith angle, which is consistent with the observation reported by Thomson and Clilverd (2001). During the solar flare, it is clearly seen that the X-ray fluxes become thoroughly dominant over both cosmic rays and Lyman-α as the ionizing source in the D by in the real unperturbed D region, galactic cosmic rays make additional ionization mainly in the lowest part (Rishbeth and Garriott 1969), so that the unperturbed electron density falls with decreasing height at a rate which is slower than for Lyman-α (or X rays) alone. Such normal unperturbed profiles, in which the electron density increases relatively slowly with height, result in relatively low values of β when modeling is done using β and H'.

Figure 5b shows variation of H' with solar flare power. In the same figure, we have also shown the results of Thomson et al. (2005). It is seen that H' shows a decreasing trend, although rate of decrease is much smaller and it is not linear. Thomson et al. (2005) reported quite sharper decrease. It is expected that the D-region electron density at low latitudes during solar flares may increase compare to mid/high latitudes. However, in contrast, we observed decrement in electron density. At low latitudes plasma dynamics is quite complex and depends on many factors such as fountain effect, meridional wind effects, equatorial electrojet associated current systems etc. (Manju et al. 2009). Hence such an enhancement/decrement may be possible. The variation of H' with intensity of solar flares, along with extrapolation is also represented by a cubic polynomial. Although, both sign and magnitude of constants differ at low latitude from those of mid latitude. The values of H' were extrapolated to fit the results of great solar flares reported by Thomson et al. (2005). The result shows that even for the quite large solar flares the effective height of the lower ionosphere may

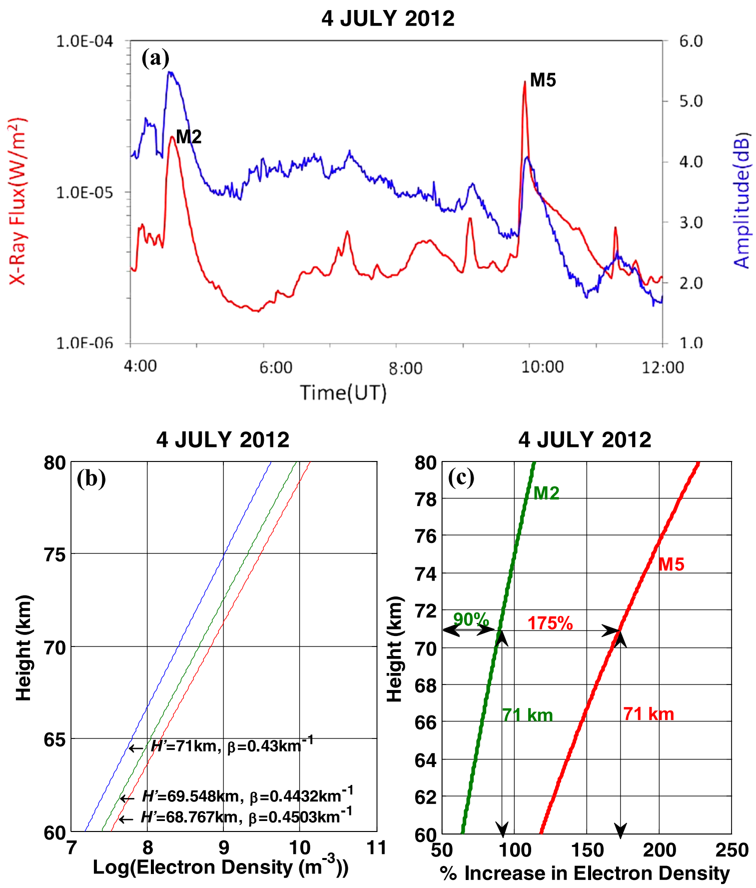

Fig. 3 (**a**) Variation of X-Ray flux and VLF signal amplitude of NWC, as received at BHU, Varanasi solar flare event of 4 July 2012. (**b**) The logarithmic electron density and (**c**) percentage increase in it with altitude during solar flare event of 4 July 2012

not come down below the altitude of 50 km. As discussed in the introduction, for nearly sunlit propagation path, Thomson (1993) found $H' = 70$ km and $\beta = 0.45\ \text{km}^{-1}$ at solar maximum while National Ocean System Centre developed LWPC program found $H' = 70$ km and $\beta = 0.5\ \text{km}^{-1}$ for 'summer'. The year, 2011–2012 are the period of the rising phase of solar cycle 24 just after the extended solar minimum, β and H' is expected to be high, but we observe relatively small values of β. H' is large as compared to that reported by Thomson et al. (2005) for solar flares of similar intensity. This lower value of β during rising phase of solar cycle 24 is likely to be due to the increased galactic cosmic rays just after the solar minimum increasing the mid-latitude electron density at heights in the lower part of the VLF reflection height range relative to the (slightly reduced) Lyman-α ionization in the upper part of this height range (Thomson and Clilverd 2001). These effects will be much less at low latitudes where the (near) horizontal geomagnetic field significantly reduces the cosmic ray intensity (Heaps 1978). Our results are important, because it pertains to the period of the rising phase of solar cycle 24 after extended solar minimum period with lesser number of sunspots. Also it belongs to low latitude equatorial anomaly region. Although the results are not consistent with the previous near solar minimum results in general at low and mid-latitudes, but they are consistent with the much lower cosmic ray intensities expected at low latitudes (or at solar maximum). It is first of its kind (using VLF signals) to study the solar flare effect at low latitude ionosphere in the Indian subcontinent at the edge of equatorial anomaly where plasma dynamics is quite complex (Mitra 1974). Previous studies such as by McRae and Thomson (2004) is a mid-latitude observation. The most intriguing aspect of these low latitude observation of solar flare is that they have small β and large H' values compared to mid and high latitude, though recorded during the rising phase of solar cycle. This shows a different mechanism of D-region plasma dynamics at low latitude during solar flare event. Therefore a comparison with mid latitude's results may give interesting information about the changes in dynamical features of the inner magnetosphere.

One of the objectives is to compare the results obtained earlier at mid/high latitudes with the measurements made at low/equatorial stations. The wave particle interaction at equatorial station is relatively less probable and hence the observability of amplitude/phase perturbations is also low. Even though we have been able to record large numbers of events. This again gives us an opportunity for studying the wave-particle interaction.

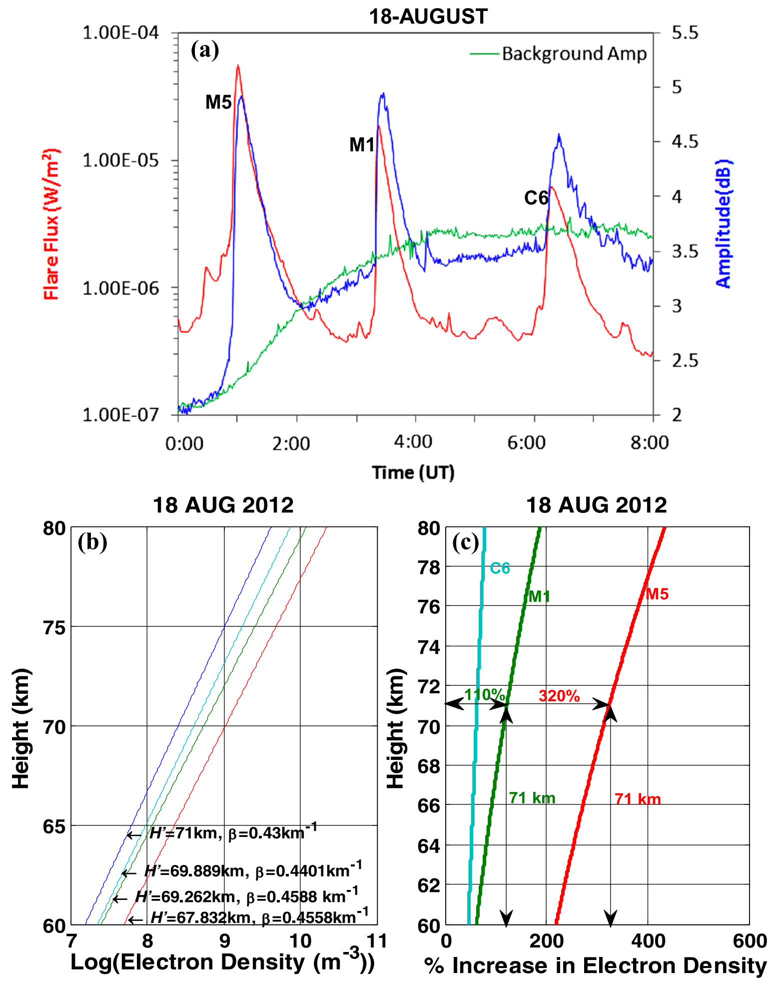

Fig. 4 (**a**) Variation of X-Ray flux and VLF signal amplitude of NWC, as received at BHU, Varanasi solar flare event of 18 August 2012. (**b**) The logarithmic electron density and (**c**) percentage increase in it with altitude during solar flare event of 18 August 2012

4 Summary and conclusion

Solar flare fluxes monitored by GOES satellite and the amplitude enhancement perturbation of the VLF signal from the NWC/18.2 kHz transmitter, received at Varanasi, have been brought into quantitative relation for the study of flare induced changes in the lower D-region ionosphere during the year 2011–2012, a period in the rising phase of solar cycle 24 with the low sunspot numbers.

The D-region changes were characterized by the two (Wait) parameters, H', as a measure of the (reflection) height in km, and β, as a measure of the sharpness or, rate of change of electron density with height in km^{-1}. It is observed that the D-region electron density shows an abrupt enhancement with the enhancement of X-ray fluxes of the solar flare events. Electron density is much more pronounced during X-class flare as compared to M-class flare. The increased ionization from the flare lowers the effective reflecting height, H', from a typical mid-day unperturbed value of about 71–72 km down to about 65 km roughly in proportion to the logarithm of the X-ray flares intensity. This lowering of effective reflection height is much above the mid latitude value ∼51–54 km showing a different mechanism of plasma dynamics at low latitude during these events. The sharpness, β, of the lower edge of the D-region is also significantly increased by the flare. It is found that β increases from around 0.43 km^{-1} (for the near midday NWC-Varanasi path) to a general saturation level of about 0.49 km^{-1}, well below the mid latitude value ∼0.51 km^{-1} (McRae and Thomson 2004). In normal, unperturbed conditions, the lower edge of the D-region is significantly contributed by galactic cosmic rays resulting in the sharpness, β in km $^{-1}$, being significantly less than if solar radiation (mainly Lyman-α) were the sole ionizing source. When X-ray fluxes from a significant solar flare arrive, they become the sole dominant source thereby producing a sharper profile and lower attenuation.

Perhaps the most intriguing aspect of these low latitude observation of solar flare is that they have small β and large H' values compared to mid and higher latitude, though being the rising phase of solar cycle 24 after extended solar minimum, should, in retrospect, be compared with the earlier (low to mid latitude) solar maximum results. Similar solar flare observations in other stations relatively close to our

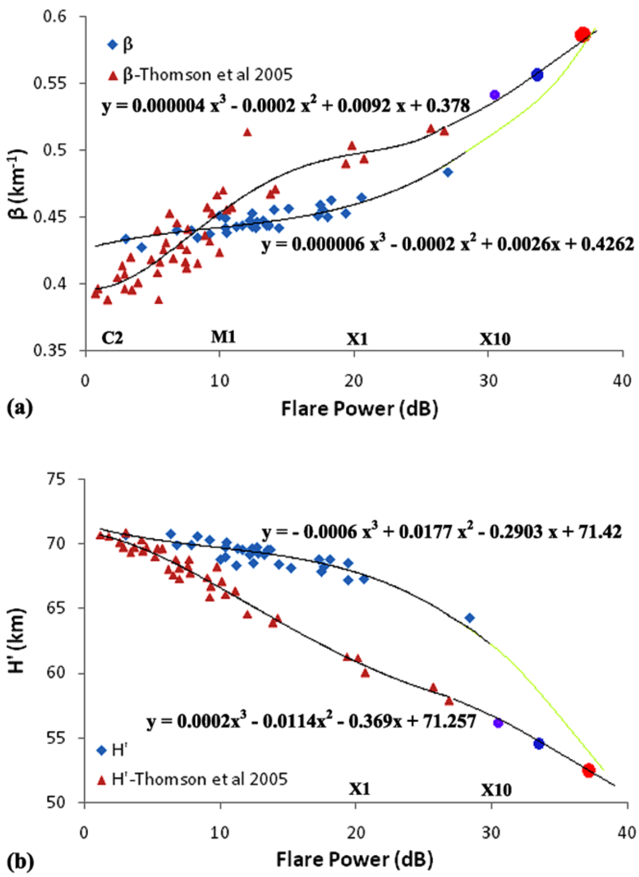

Fig. 5 (**a**) Variation of sharpness factor, β as a function of solar flare X-ray intensity during the year 2011–2012. *Purple*, *blue* and *red circles* shown on the Thomson et al. (2005) curve shows three very large solar flares: X10 of 29 Oct 03, X20 of 2 April 01 and X45 of 04 Nov 03 respectively reported by them. *Green line* shows the extrapolated values of β with flare power. The equations for the two curves are also shown (**b**) Variation of virtual reflection height, H' as a function of solar flare X-ray intensity observed during 2011–2012. *Purple*, *blue* and *red circles* shown on the Thomson et al. (2005) curve shows three very large solar flares: X10 of 29 Oct 03, X20 of 2 April 01 and X45 of 04 Nov 03 respectively reported by them. *Green line* shows the extrapolated values of H' with flare power. The equations for the two curves are also shown

low latitude site, Varanasi and the investigation of long term variation with more theoretical modeling would help to elucidate the potential role of the flares on D-region conductivity and ionospheric parameters.

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