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ORIGINAL ARTICLE

Effective recombination coefficient and solar zenith angle effects on low-latitude D-region ionosphere evaluated from VLF signal amplitude and its time delay during X-ray solar flares

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Abstract Excess solar X-ray radiation during solar flares causes an enhancement of ionization in the ionospheric D-region and hence affects sub-ionospherically propagating VLF signal amplitude and phase. VLF signal amplitude perturbation (ΔA) and amplitude time delay (Δt) (vis-á-vis corresponding X-ray light curve as measured by GOES-15) of NWC/19.8 kHz signal have been computed for solar flares which is detected by us during Jan–Sep 2011. The signal is recorded by SoftPAL facility of IERC/ICSP, Sitapur (22° 27′N, 87° 45′E), West Bengal, India. In first part of the work, using the well known LWPC technique, we simulated the flare induced excess lower ionospheric electron density by amplitude perturbation method. Unperturbed D-region electron density is also obtained from simulation and compared with IRI-model results. Using these simulation results and time delay as key parameters, we calculate the effective electron recombination coefficient (α_{eff}) at solar flare peak region. Our results match with the same obtained by other established models. In the second part, we dealt with the solar zenith angle effect on D-region during flares. We relate this VLF data with the solar X-ray data. We find that the peak of the VLF amplitude occurs later than the time of the X-ray peak for each flare. We investigate this so-called time delay (Δt). For the C-class flares we find that there is a direct correspondence between Δt of a solar flare and the average solar zenith angle Z over the signal propagation path at flare occurrence time. Now for deeper analysis, we compute the Δt for different local diurnal time slots DT. We find that while the time delay is anti-correlated with the flare peak energy flux ϕ_{max} independent of these time slots, the goodness of fit, as measured by *reduced*-χ^2, actually worsens as the day progresses. The variation of the Z dependence of *reduced*-χ^2 seems to follow the variation of standard deviation of Z along the T_x-R_x propagation path. In other words, for the flares having almost constant Z over the path a tighter anti-correlation between Δt and ϕ_{max} was observed.

Keywords X-ray solar flare · Time delay · Recombination coefficients · D-region ionosphere

1 Introduction

The ionosphere of the earth is a gigantic detector and it characteristically responds to the ionizing agents of terrestrial and extra-terrestrial origin. In particular, it is long known that the hard and soft X-rays originating from solar flares (Mitra 1974; Pant 1993) and strong compact celestial sources like X-ray novae, galactic centre do perturb the lower ionospheric D-region (Sharma et al. 1972; Kasturirangan et al. 1976). The excess EUV and X-ray radiations produced during the solar flares cause excess ionization (Basak et al. 2010; Garcia-Rigo et al. 2007; Chakrabarti et al. 2012). This manifests in an enhancement of the free electron density of the D-region by several orders of magnitude than the normal value. This is primarily due to the electron detachment from nitrogen and oxygen (Thomson and Clilverd 2001). The main physical mechanism behind the ionospheric effects of the solar flares have been discussed by Mitra (1974). A comparative study between the changes of VLF signal amplitude (and phase) and solar X-ray flux has been made by several workers such as Ananthakrishnan et al. (1973) and Pant (1993).

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