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Probing geomagnetic storm-driven magnetosphere–ionosphere dynamics in D-region via propagation characteristics of very low frequency radio signals

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ABSTRACT

The amplitude and phase of VLF/LF radio signals are sensitive to changes in electrical conductivity of the lower ionosphere which imprints its signature on the Earth–ionosphere waveguide. This characteristic makes it useful in studying sudden ionospheric disturbances, especially those related to prompt X-ray flux output from solar flares and gamma ray bursts (GRBs). However, strong geomagnetic disturbance and storm conditions are known to produce large and global ionospheric disturbances, which can significantly affect VLF radio propagation in the D region of the ionosphere. In this paper, using the data of three propagation paths at mid-latitudes (40–54°), we analyse the trend in variation of aspects of VLF diurnal signal under varying solar and geomagnetic space environmental conditions in order to identify possible geomagnetic footprints on the D region characteristics. We found that the trend of variations generally reflected the prevailing space weather conditions in various time scales. In particular, the 'dipping' of mid-day signal amplitude peak (MDP) occurs after significant geomagnetic perturbed or storm conditions in the time scale of 1–2 days. The mean signal amplitude before sunrise (MBSR) and mean signal amplitude after sunset (MASS) also exhibit storm-induced dipping, but they appear to be influenced by event's exact occurrence time and the highly variable conditions of dusk-to-dawn ionosphere. We also observed few cases of the signals rise (e.g., MDP, MBSR or MASS) following a significant geomagnetic event. This effect may be related to storms associated phenomena or effects arising from sources other than solar origin. The magnitude of induced dipping (or rise) significantly depends on the intensity and duration of event(s), as well as the propagation path of the signal. The post-storm day signal (following a main event, with lesser or significantly reduced geomagnetic activity) exhibited a tendency of recovery to pre-storm day level. In the present analysis, we do not see a well-defined trend in the variation of the post-storm sunrise amplitude terminator (SRT) and sunset terminator (SST). The SRT and SST signals show more dipping in GQD-A118 propagation path but generally an increase along DHO-A118 propagation path. Thus the result could be propagation path dependent and detailed modelling is required to understand these phenomena.

1. Introduction

Although separated by thousands of kilometers, the magnetosphere and ionosphere are known to be physically connected (through the Earth's magnetic field) into one global system. The ionosphere responds to (a) prompt changes in solar energetic events, mainly the solar flare associated bursts in EUV, X-ray and relativistic particles (Mitra, 1974; Buonsanto, 1999; Alfonsi et al., 2008), (b) delayed changes mainly due to geomagnetic storm conditions with time scale from several hours to 1–3 days (Lastovicka, 1996; Buonsanto, 1999; Kutiev et al., 2013), and (c) periodic changes with time scales of several days to months, and those of several solar cycles (Alfonsi et al., 2008; Kutiev et al., 2013). The ionosphere also exhibits diurnal (day/night) and seasonal (e.g. summer/winter) variations (Miller and Brace, 1969; Zhang et al., 1999). Solar and geomagnetic induced phenomena drive changes in magnetosphere conditions, whose coupling effects modify ionospheric signatures including atmospheric density distribution, total electron content (TEC), ionospheric current

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system, ionisation rates, and crucial D-region parameters such as conductivity gradient and reference height (Wait, 1959; Wait and Spies, 1964; Mitra, 1974; Buonsanto, 1999; Burke, 2000; Simoes et al., 2012; Nwankwo and Chakrabarti, 2014). The dynamics of ionospheric response to changes in solar and geomagnetic conditions involve the exchange of particles and electromagnetic energy (absorbed, reprocessed and deposited in the ionosphere by the magnetosphere) between magnetically connected regions (Burke, 2000; Streltsov and Lotko, 2004; Goldstein et al., 2005; Russell et al., 2010; Russell and Wright, 2012; Leonard et al., 2012; Kutiev et al., 2013).

1.1. The ionosphere at a glance

The ionosphere is composed of three distinct space regions [D (50–90 km), E (90–120 km), and the F (from 120 km up to 500 km), which often split into two layers, namely, F1 and F2]. Its existence is primarily due to ionisation by solar ultraviolet (UV) radiation and X-ray wavelength (Kelley, 1989; Prolss, 2004; McRae and Thomson, 2004; Raulin et al., 2006; Heikkila, 2011) and isotropic cosmic rays. Recombination also occurs when free electrons are captured by positive ions. Ionisation and recombination efficiency controls the overall electron density at every time instant. The D region ionosphere is highly active during the day (roughly between the local sunrise and sunset) due to high rate of ionisation, but its density falls significantly at night largely due to rapid recombination at the altitude. The E region also maintains the same dynamics (night/day fluctuations) as the D region but ionisation state persists longer due to slower rate of recombination at lower density. Thus, the reflection of signals mainly occurs at the bottom of the nighttime E region (Han and Cummer, 2010 and references therein). The F region is present both day and night; air density and recombination rate is very low in the region. Therefore, ionisation persists in the nighttime (also see Mimno, 1937; Poole, 1999; Prolss, 2004). In general, these layers are severely disturbed by phenomena of solar and geomagnetic origin, as well as planetary and tidal waves, thermospheric tides and stratospheric warming (Pancheva et al., 2008; Leonard et al., 2012; Chen et al., 2013; Goncharenko et al., 2012; Polyakov et al., 2014). However, effects at different heights, locations or latitudes vary in development, depending on time and intensity (of driving force). Ionospheric signature variations reflect different mechanisms and aspects of solar and other induced phenomena.

1.2. VLF propagation in the Earth–ionosphere waveguide

The velocity, direction and amplitude of most electromagnetic waves are distinctly affected when propagating through the ionosphere. This characteristic makes radio waves an ideal tool for ionospheric study (Prolss, 2004). Very low frequency (VLF) radio waves in the 3–30 kHz are effective in the investigation of solar induced variable conditions in the ionosphere (especially the D region) because their amplitude and phase are sensitive to changes in electrical conductivity of the lower ionosphere (Wait and Spies, 1964; Mitra, 1974; Alfonsi et al., 2008). VLF radio signals are reflected alternately by the D region and the Earth's surface due to high conductivity (Mimno, 1937; Poole, 1999). The transmitted wave is thus guided between the Earth and the ionosphere enabling the signal to propagate globally through the Earth–ionosphere waveguide. The signal is then received at various receivers across the world. Variations in daytime VLF signal amplitude and phase appear to be well correlated with solar X-ray output, with almost prompt responses. Hence, it has been used by many researchers to study sudden ionospheric disturbances and changes in the atmosphere (e.g., Araki, 1974; Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Kleimenova et al., 2004; McRae and Thomson, 2004; Thomson et al., 2004; Chakrabarti et al., 2005; Grubor et al., 2005; Peter et al., 2006; Sasmal and Chakrabarti, 2009; Chakrabarti et al., 2010; Clilverd et al., 2010; Raulin et al., 2006, 2010; Basak et al., 2011; Pal et al., 2012; Palit et al., 2013; Ray and Chakrabarti, 2012; Raulin et al., 2013; Nwankwo and Chakrabarti, 2014). Other methods used for ionospheric studies include observational and experimental techniques and tools such as Global Navigation Satellite system (GNSS) receivers, vertical and oblique sounding, Riometers, incoherent scatter radars (e.g., EISCAT), coherent scatter radars (e.g., Goose Bay radar, SuperDARN), magnetometers, etc. (Greenwald et al., 1995, 1996; Honary et al., 1995; Lastovicka, 1996; Wild et al., 2003; Burke, 2000; Danilov and Lastovicka, 2001; Goldstein et al., 2005; Ruohoniemi and Greenwald, 2005; Alfonsi et al., 2008).

1.3. VLF signal detection mechanism of sudden ionospheric disturbances

The D region ionosphere is maintained by Lyman-α radiation at a wavelength of about 121.5 nm, which ionises neutral nitric oxide (NO). With high solar activity, hard X-ray ($\lambda < 1$ nm) may ionise N_2 and O_2. Galactic cosmic rays are also responsible for the ionisation of the lowest part of the lower ionosphere and the low-lying atmosphere down to the troposphere (also, see Mitra, 1974; Lastovicka, 1996). A huge amount of energy is released during solar flare in the form of highly energetic ultraviolet radiation, mainly X-ray flux enhancement. The radiation penetrates the D region where it increases ionisation rate (of dominant neutral NO molecules), and enhances electron density. These processes enhance the ‘thickness’ of the D region, thereby decreasing the reflection height (h) in the waveguide. This is normally detected as a sudden change (usually an increase) in the amplitude and phase enhancement of a VLF signal. VLF dusk-to-dawn signal exhibits high variability (or fluctuation) due to a significant fall in density of the D region. The signal is also sensitive to phenomena other than those originating from the Sun. Day time VLF signal is primarily controlled by the Sun.

1.4. Geomagnetic induced variations of the ionosphere and effects

Geomagnetic disturbances and storms are also known to produce significant global disturbances in the ionosphere, including the middle atmosphere and troposphere (Lastovicka, 1996; Danilov and Lastovicka, 2001). Geomagnetic storms are the products of highly variable solar wind speeds and density and associated shock waves (Lastovicka, 1989; Baker, 1996, 2000; Borovsky and Denton, 2006; Tsurutani et al., 2006; Kozyra et al., 2006). The effects of geomagnetic storms on the ionosphere manifest mainly through energetic particles precipitation, which lose their energy by impact and X-ray bremsstrahlung production (Lastovicka, 1996). There is also a consequent and significant enhancement of electron density (Chenette et al., 1993; Stoker, 1993; Lastovicka, 1996), causing significant increase in radio wave absorption and subsequent disappearance of radio signals in MF/HF values (Lastovicka, 1996). Galactic cosmic ray flux (which are modulated by geomagnetic storms) and global electric circuit and atmosphere electricity (affected by local changes of conductivity and ionosphere/magnetosphere electric fields and currents) are assumed to be the processes for ionospheric effects of geomagnetic storms (Danilov and Lastovicka, 2001). VLF signals can be significantly affected by geomagnetic disturbances and storms induced ionosphere perturbations (Kikuchi and Evans, 1983). Nevertheless, a few researchers have used it to study these perturbations with insightful findings (e.g., Araki, 1974; Kleimenova et al., 2004; Peter et al., 2006; Clilverd et al., 2010; Kumar and Kumar, 2014; Tatsuta et al., 2015).