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Advances in Space Research 54 (2014) 2236–2248

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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The asymmetrical features in electron density during extreme solar minimum

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Received 25 March 2014; received in revised form 25 August 2014; accepted 26 August 2014
Available online 6 September 2014

Abstract

The variations of plasma density in topside ionosphere during 23rd/24th solar cycle minimum attract more attentions in recently years. In this analysis, we use the data of electron density (Ne) from DEMETER (Detection of Electromagnetic Emissions Transmitted from Earthquake Regions) satellite at the altitude of 660–710 km to investigate the solstitial and equinoctial asymmetry under geomagnetic coordinate system at LT (local time) 1030 and 2230 during 2005–2010, especially in solar minimum years of 2008–2009. The results reveal that ΔNe (December–June) is always positive over Southern Hemisphere and negative over northern part whatever at LT 1030 or 2230, only at 0–10°N the winter anomaly occurs with ΔNe (December–June) > 0, and its amplitude becomes smaller with the declining of solar flux from 2005 to 2009. The ΔNe between September and March is completely negative during 2005–2008, but in 2009, it turns to be positive at latitudes of 20°S–40°N at LT 1030 and 10°S–20°N at LT 2230. Furthermore, the solstitial and equinoctial asymmetry index (AI) are calculated and studied respectively, which all depends on local time, latitude and longitude. The notable differences occur at higher latitudes in solar minimum year of 2009 with those in 2005–2008. The equinoctial AI at LT 2230 is quite consistent with the variational trend of solar flux with the lowest absolute AI occurring in 2009, the extreme solar minimum, but the solstitial AI exhibits abnormal enhancement during 2008 and 2009 with bigger AI than those in 2005–2007. Compared with the neutral compositions at 500 km altitude, it illustrates that [O/N_2] and [O] play some roles in daytime and nighttime asymmetry of Ne at topside ionosphere.

Keywords: Electron density; Topside ionosphere; Solstitial asymmetry; Equinoctial asymmetry

1. Introduction

The temporal and spatial variations of the plasma parameters at the peak layer and topside ionosphere have been widely studied for many years from the ground-based and satellite observation, and some anomalous phenomena in ionosphere have been revealed in many researches, such as the annual asymmetry in plasma density between winter and summer, and equinoctial asymmetry between two equinoxes (Rishbeth and Müller-Wodarg, 2006; Balan et al., 1998). King (1961) found the seasonal anomaly in the critical frequency in F2 layer (foF2), whereby the winter noon values are greater than the summer ones. Torr and Torr (1973) provided the global map of the winter anomaly using NmF2 data from worldwide ionosonde stations, with the 'winter anomaly' (bigger Ne in winter than in summer) more pronounced during the solar maximum period and in the Northern Hemisphere. Observations made by the middle and upper atmosphere (MU) radar in Japan show the gradual disappearance of the winter anomaly feature with an increase in altitude above the F-peak height (Balan et al., 1998, 2000; Kawamura et al., 2002). By analyzing the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites, Lee et al. (2011) investigated into the altitude, local time, latitude,

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http://dx.doi.org/10.1016/j.asr.2014.08.028
0273-1177/

longitude, and hemispheric variations of the electron density in the middle-latitude ionosphere in 2007 under low solar activity, and they found the winter anomaly feature during LT 0800–1600 in the Northern Hemisphere but not in the Southern Hemisphere. Liu et al. (2007) obtained the solstitial asymmetry feature with larger Ni in the Southern Hemisphere in December solstice than that in the Northern Hemisphere at June solstices by DMSP spacecraft during 1996–2005, and they thought that the change of [O] and the rates of thermospheric winds should contribute to the annual asymmetry in Ni at 840 km altitude. Previous studies have proposed some assumptions to explain the annual asymmetry, such as the seasonal changes of atmospheric compositions produced by a global circulation (Duncan, 1969; Millward et al., 1996), and also the geometrical explanations, the thermal explanations, the chemical explanations (Rishbeth, 1998; Zou et al., 2000), but causes for the annual asymmetry is still not completely understood (Mendillo et al., 2005). Based on these researches, it is known that the annual asymmetry is closely related to local time and altitudes. The previous studies have been concentrated on the plasma parameters at peak height of ionosphere, while the studied altitude of COSMIC satellite was less than 500 km, so the research on topside ionosphere at altitude 600–700 km hopes to make up for gaps in this topic.

With the further research on the global patterns and underlying physical processes on the summer-to-winter differences, more and more interests have been attracted on the equinoctial asymmetry. Essex (1977) found that the total electron content (TEC) in the spring equinox (March–April) is usually higher than that in the autumn equinox (September–October) at several stations. Titheridge (1973) and Bailey et al. (2000) reported the equinoctial asymmetry in the topside electron density, and the results by Hinotori satellite data of Bailey et al. (2000) illustrated that the asymmetry was hemisphere-dependent with the higher Ne occurring at the March equinox in the Northern Hemisphere and at the September equinox over the Southern Hemisphere, as while the asymmetry became stronger with increasing latitude at both hemispheres. Wan et al. (2008) also showed an equinoctial asymmetry in longitudinal wave number 4 structures, with the wave intensity stronger in northern autumn months than in spring. Liu et al. (2010) studied the altitudinal dependence of the equinoctial asymmetry in ionosphere around LT 1400 during low solar activity by using the ionospheric electron density profiles and TEC data. Liu et al. (2007) obtained pronounced equinoctial differences in the thermospheric mass density with larger values in the March equinox than in the September equinox at all latitudes. And the effect of neutral wind may explain the northern low latitude equinoctial asymmetry (Balan et al., 2000), but it fails in the Southern Hemisphere (Liu et al., 2010). The solar activity during 2008–2009 is a prolonged minimum among several recent solar cycles, thereby providing a unique opportunity to explore the response of the ionosphere and thermosphere under this extreme condition. The minimum of solar cycle 23rd/24th was quite special for its absence of sunspots for a number of days (Livingston and Penn, 2009). The patterns and its physical processes in equinoctial asymmetry during this solar minimum have not been studied previously.

DEMETER satellite had been operated for more than 6 years with a sun-synchronous orbit at the altitude of 660–710 km since the end of June in 2004 to the early December in 2010 (Cussac et al., 2006), which covered the extreme solar minimum in the 23rd/24th solar cycles. From this satellite, topside plasmas were continuously detected by ISL (Instrument Sonde de Langmuir) and IAP (Instrument d'Analyse du Plasma) instruments (Lebreton et al., 2006; Berthelier et al., 2006), which provides a good opportunity for studying the asymmetrical features at difference seasons over Southern and Northern Hemispheres in solar minimum. Due to the time coverage limitation of DEMETER, in this paper we will concentrate on the study of the asymmetrical features at LT 1030 and 2230, respectively based on the observing plasma data, and analyze their temporal variations year-by-year during 2005–2010 under the low and minimum solar activity condition. By this study, the behavior of topside ionosphere can be obtained at the specific altitude and local time, and the altitude of DEMETER and its global coverage at stable local time are totally different with other satellites, which can effectively make up for the gaps in topside ionosphere. Moreover the relationship between the inter-hemispheric asymmetry and solar flux will be revealed especially under this extreme solar minimum, which will provide more information to further understand the forming mechanism of inter-hemispheric asymmetry and coupling processes between ionosphere and upper atmosphere.

2. The spatial distribution of electron density during solar minimum

In previous research (Zhang et al., 2013), the solar cycle variation features in Ne have been studied in local daytime and nighttime respectively from DEMETER satellite during 2005–2010, and the results showed globe Ne decreased with the reducing solar flux since 2005 to 2009. While there exhibited phase shift at middle latitudes and even reversed annual variations at high latitudes over Southern and Northern Hemisphere, and the annual variation amplitudes were asymmetrical over two hemispheres. Fig. 1 presents the spatial distribution of Ne at local daytime 1030 and nighttime 2230 in three seasons with equinoxes (including March–April, and September–October), June solstice (May–August) and December solstice (November–December and January–February) in solar minimum year of 2008 by geomagnetic coordinate system. From Fig. 1(a), the daytime Ne shows large differences at three seasons, with the lowest Ne occurring in June solstice. Compared with pictures in two solstices, besides the difference near the equator, much higher Ne also occurred at the southeast part in December solstice, but in June solstice, Ne over