Icarus 251 (2015) 5–11

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Variations in peak electron densities in the ionosphere of Mars over a full solar cycle

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ARTICLE INFO

Article history:
Received 19 February 2014
Revised 24 June 2014
Accepted 11 August 2014
Available online 23 August 2014

Keywords:
Mars
Ionosphere
Solar radiation

ABSTRACT

Peak electron densities in the ionosphere of Mars are strongly influenced by the intensity of ionizing solar flux and hence by the solar cycle. Datasets used in previous studies of this relationship have incompletely sampled the range of solar irradiances encountered over a full solar cycle. Here, thousands of Mars Global Surveyor radio occultation measurements and hundreds of thousands of Mars Express topside radar sounder measurements from 1998 to 2013 are used to test whether the conclusions of previous workers withstand a substantial increase in the number of datapoints and near-continuous sampling across a range of ionizing solar irradiances. Data from narrow ranges in solar zenith angle (70°–80°) and latitude (60°N–80°N) are used in order to isolate, to the extent possible, the influence of irradiance. Ionospheric peak electron density increases smoothly with increasing F10.7, but this increase saturates at F10.7 values above 130 units. However, in contrast to some previous work, there is no change in behavior at an F10.7 value of 100 units. Saturation at high values of F10.7 also occurs in Earth's ionosphere and the underlying cause is that the appropriateness of F10.7 as a proxy for ionizing solar irradiance diminishes at high solar activity. Similar overall trends are seen when the Lyman alpha emission or the Mg II core-to-wing index are used to replace F10.7 as a proxy for ionizing solar irradiance. Even when solar zenith angle and latitude are restricted, a time series of electron density residuals shows noteworthy trends. These trends might indicate a dependence of peak density on season, but they are not caused by changes in the Mars–Sun distance.

1. Introduction

Orbital spacecraft have continuously operated at Mars since the arrival of Mars Global Surveyor (MGS) in 1997. These missions (Mars Global Surveyor, Mars Odyssey, Mars Express (MEX), Mars Reconnaissance Orbiter) have provided long-term monitoring of a host of features related to the geology, climate, and space environment of Mars. Ionospheric observations have been provided by radio occultation observations by MGS and MEX (Hinson et al., 1999; Pätzold et al., 2005) and by topside radio sounder observations by the MARSIS instrument on MEX (Gurnett et al., 2005, 2008). Both types of observations determine the peak electron density in the dayside ionosphere, which is the single most useful diagnostic of the state of the ionosphere and the focus of this work.

Dayside electron densities in the ionosphere are affected by the solar cycle, with densities increasing as ionizing solar irradiance increases. Many workers have investigated how peak electron density changes with various representations of the ionizing solar irradiance (Hantsch and Bauer, 1990; Breus et al., 2004; Withers and Mendillo, 2005; Zou et al., 2006; Morgan et al., 2008; Fox, 2004; Fox and Yeager, 2006, 2009; Němec et al., 2011; Girazian and Withers, 2013). However, due to limited amounts of data, none have yet looked at variations in peak electron density with time over a full solar cycle.

Here we investigate how peak electron densities observed by MGS radio occultations and MEX topside radar sounding observations from MARSIS vary with time from 1998 to 2013. This period encompasses a strong solar maximum in 2000 and a remarkably prolonged and deep solar minimum centered on 2008. Our primary objective is to test whether the conclusions of previous workers withstand a substantial increase in the number of datapoints and near-continuous sampling across a range of ionizing solar irradiances. Secondary objectives are to investigate whether changes in season and local solar time have significant effects on peak electron density.

Fig. 1 shows solar conditions, the Mars–Sun distance, martian season, observed solar zenith angle, and observed latitude during this period. Times are described by "Day of year 1998" such that

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http://dx.doi.org/10.1016/j.icarus.2014.08.008
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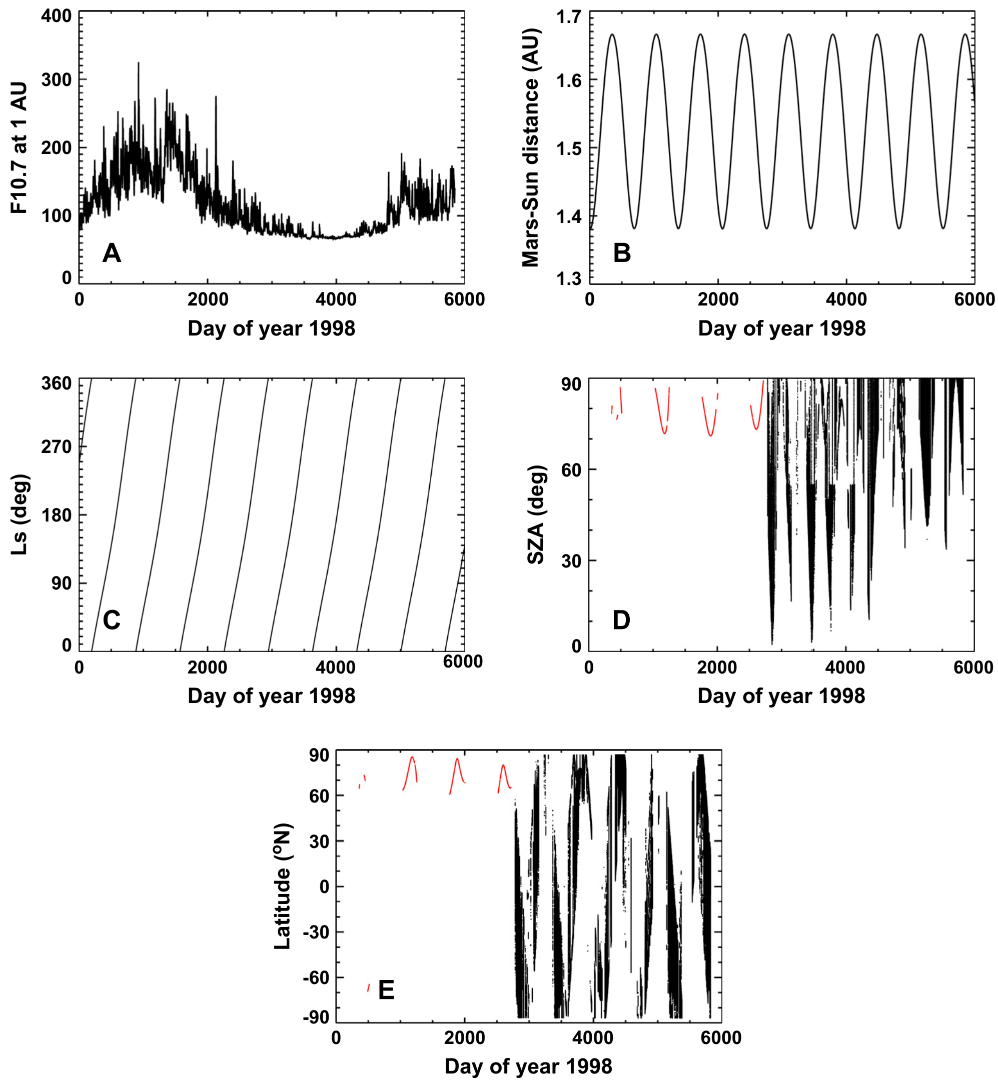

Fig. 1. A. Solar irradiance at 1 AU. These F10.7 values were obtained from the National Geophysical Data Center, ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-radio/noontime-flux/penticton/penticton_adjusted/listings/listing_drao_noontime-flux-adjusted_daily.txt. B. Mars–Sun distance. C. Ls, a measure of martian season. D. Solar zenith angle of ionospheric observations by MGS radio occultations (red) and MARSIS (black). E. Latitude of ionospheric observations by MGS radio occultations (red) and MARSIS (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1 January 1998 equals 1 and 31 December 2013 equals 5843. Fig. 1 uses the value of F10.7 at 1 AU to illustrate variations in the ionizing solar irradiance over time. This solar irradiance proxy is admittedly imperfect, but has the advantage of being widely used in prior work (e.g., Hantsch and Bauer, 1990; Morgan et al., 2008) and available over many decades (Girazian and Withers, 2013). Other proxies for the ionizing solar irradiance are discussed later in this work (Section 3).

Section 2 introduces the two datasets, MGS radio occultations and MARSIS topside radar soundings, and describes the preparation of the data. Section 3 describes trends in electron densities over the solar cycle (Section 3.1) and interprets the residual differences between observations and a fit to the observations (Section 3.2). Section 4 presents our conclusions.

2. Observations and data preparation

MGS radio occultations determined 5600 electron density profiles at solar zenith angles less than 90°. The dates, latitudes, and solar zenith angles (SZAs) sampled by this dataset are listed in Table 1 of Withers et al. (2008) (Fig. 1). These data were acquired from the Planetary Data System (Hinson, 2007). Previous workers have used these observations to track tides in the neutral thermosphere (Bougher et al., 2001, 2004), to characterize the ionospheric effects of crustal magnetic fields (Withers et al., 2005), to study layers of meteoric plasma (Withers et al., 2008), and to investigate the ionospheric effects of the changing solar irradiance (Withers and Mendillo, 2005; Mendillo et al., 2006; Girazian and Withers, 2013). The 5600 peak electron densities are shown in the top panel of Fig. 2.

MARSIS topside radar sounding produced over 140,000 ionograms at solar zenith angles less than 90° between 14 August 2005 and 12 December 2013. Previous workers have used these observations to discover ionospheric bulges over regions of strong crustal magnetic fields (Duru et al., 2006), to characterize a sporadic layer in the topside ionosphere (Kopf et al., 2008), to detect the ionopause (Duru et al., 2009), to monitor the radio wave attenuation caused by solar energetic particle events (Morgan et al., 2006, 2010), to explore the nightside ionosphere (Němec et al., 2010, 2011; Duru et al., 2011), to develop an empirical model of ionospheric densities (Němec et al., 2011), to quantify the ionospheric effects of seasonal and solar variations (Morgan et al.,