Icarus 221 (2012) 1002–1019

Contents lists available at SciVerse ScienceDirect

Icarus

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

MGS electron density profiles: Analysis and modeling of peak altitudes

Jane L. Fox *, Andrew J. Weber

Department of Physics, Wright State University, Dayton, OH 45435, United States

ARTICLE INFO

Article history:
Received 17 July 2012
Revised 2 October 2012
Accepted 3 October 2012
Available online 23 October 2012

Keywords:
Mars
Ionospheres
Aeronomy
Terrestrial planets

ABSTRACT

We have analyzed most of the electron density profiles returned from the Mars Global Surveyor Radio Science Experiment, with a view toward investigating the shapes of the profiles and the altitudes of the upper (F_1) and lower (E) peaks as a function of solar zenith angle and solar activity. We first categorize the shapes of the profiles according to the morphology of the F_1 and E peaks, and find that there is an expected variation with solar activity of the two major types of shapes, those in which the E-peak appears as a shoulder on the bottomside of the F_1 peak, and those in which the E peak is separated by a small minimum from the F_1 peak. Since the peak altitudes have been shown to vary with planetocentric longitude, we divide the data into 36 10°E. longitude bins. We have plotted the peak altitudes of both the upper and lower peaks as a function of ln(effective secant χ), where χ is the solar zenith angle. The "effective secant" is derived by integrating the densities along the line of sight to the Sun and dividing the result by the vertically integrated densities. We then fit the peak altitudes in each longitude bin with linear least squared regressions, and report the slopes and intercepts of the lines, which, in Chapman theory, correspond to the scale heights and the subsolar peak altitudes, respectively. We find that both parameters are highly variable, and the median slopes for the F_1 and E peaks are about 7 and 4 km, respectively. If interpreted as a scale height, the latter value implies a temperature in the unrealistic range of 70–75 K. In Chapman theory, there is no solar activity variation of the peak heights. When we plot the peak altitudes versus $F_{10.7}$ for each longitude bin, however, and fit them to a trendline, we find that the mean slopes are negative for both the F_1 and E peaks, although the slopes are in general smaller for the F_1 peaks. We conclude that the E peak heights are inversely correlated with solar activity, but the evidence is not as strong for the F_1 peaks. We compare electron density profiles from a numerical model to Chapman profiles, and show that the fit is poor for one Chapman profile, but is improved with a superposition of two Chapman profiles, although there are still large deviations, especially on the topside. Finally, we plot the peaks of the near-terminator numerical models for low and high solar activities as a function of ln(effective secant χ), and find that the linear fits appear to be good, but the slopes are not indicative of the scale heights in our models, nor are the intercepts the same as the peak heights of our 0° models. We conclude from these various studies that there is considerable evidence for non-Chapman behavior in the ionosphere of Mars.

1. Introduction

1.1. General background

The Mars Global Surveyor (MGS) spacecraft was launched in November, 1996 and arrived at Mars in September, 1997. After several months of aerobraking, it achieved its final near polar, circular orbit (e.g., Albee et al., 1998). Among the suite of instruments that was carried to Mars was the Radio Science Subsystem (RSS), which provided profiles of the pressure and temperature in the lower atmosphere, and of electron densities in the ionosphere (e.g., Hinson et al., 1999, Tyler et al., 2001). The MGS RSS electron density profiles are available on a CD from the Planetary Data System (Hinson and Simpson, 2008). A total of 5600 ionospheric radio occultation (RO) profiles were returned by the instrument in seven seasons between 1998 December and 2005 June. Six of the seven seasons were in the northern hemisphere in the latitude range 60.6–85.5°. The solar zenith angle (SZA) range for these occultations is about 71–89.2°. The 220 occultations in season 3 were in the southern hemisphere, where the latitude ranged from −60.6° to −69.9°, and the SZA ranged from 78.5° to 86.9°. Although the lack of data for smaller SZAs imposes some limitations, the MGS RO profiles have provided an unprecedented opportunity to investigate the dayside near-terminator martian ionosphere.

Most of the electron density profiles in the ionosphere of Mars are characterized by an upper F_1 peak, and a lower E-region peak. For SZAs in the range of the MGS RSS electron

* Corresponding author.
E-mail address: jane.fox@wright.edu (J.L. Fox).

0019-1035/$ - see front matter
http://dx.doi.org/10.1016/j.icarus.2012.10.002

density profiles, the F_1 peak usually appears between about 130 and 140 km, with a median altitude of 135.5 km, and the *E*-region peak appears between about 108 and 120 km, with a median altitude of 114.1 km. The *E*-region peak is usually seen as a shoulder on the lower side of the F_1 peak or as a more-or-less distinct peak below a small minimum in the electron density profile. This is also true for most of the RO electron density profiles returned from earlier spacecraft, such as the Mariner 6 and 7 flybys (e.g., Fjeldbo and Eshleman, 1968, Fjeldbo et al., 1970, Hogan et al., 1972); the Soviet Mars-2 orbiter, and the Mars-4 and Mars-6 flybys (e.g., Kolosov et al., 1973, 1975, Vasil'ev et al., 1975); the Mariner 9 orbiter (e.g., Kliore et al., 1972a, 1973; Kliore, 1974); and the Viking 1 and 2 orbiters (e.g., Lindal et al., 1979; Kliore, 1992; Zhang et al., 1990). These early missions returned fewer RO profiles, but in general, they covered a greater range of SZA, for which the geometrical minimum is near 45°. The only in situ data available for individual ion densities are those measured by the retarding potential analyzers (RPAs) on the Viking 1 and 2 landers near 44° SZA (Hanson et al., 1977). The Viking RPA data show only a single O_2^+ peak near 130 km, but no lower peak. Hanson et al. (1977) advised that, although the RPA attempted to detect ions near 112 km, problems related to the short mean free path at low altitudes limited the accuracy of the density profiles to altitudes above 120 km. Therefore, a lower peak or shoulder could easily have escaped detection. The two-peaked structure of the ionosphere has been modeled by, for example, Fox and Dalgarno (1979), Fox et al. (1995), Bougher et al. (2001), Krasnopolsky (2002), Martinis et al. (2003), Fox (2004), and Fox and Yeager (2006).

Our nomenclature for the two peaks is based on the nature of their production mechanisms, and is consistent with those of, for example, Bauer (1973), Banks and Kockarts (1973), Stewart and Hanson (1982), and Bauer and Lammer (2004). The F_1 or upper peak is produced mostly by ionization by solar photons in the main region of the solar EUV (∼200–1000 Å). Ionization by the more energetic EUV solar photons produces photoelectrons that also contribute to ionization; the peak of the electron-impact ionization profile appears on the lower side of the F_1 photoionization peak, which acts to broaden and lower the peak. Ionization in the region of the *E* peak is produced initially by photoionization by soft X-rays (∼10–150 Å), and subsequently by the concomitant very energetic photoelectrons, secondary, Auger, and further ionizing electrons. In fact, electron impact ionization is the major source of the *E* layer.

Other investigators have used different nomenclature for the two main peaks, calling the lower or *E*-region peak "M1" and the upper or F_1 peak "M2" (e.g., Martinis et al., 2003; Mendillo et al., 2003, 2006; Rishbeth and Mendillo, 2004; Withers and Mendillo, 2005; Withers, 2009). Rishbeth and Mendillo (2004) showed, however, that the terrestrial F_1 shoulders and the *E* region peaks appeared at the same pressure levels as the Mars "M2" and "M1" peaks, respectively, and that they responded similarly to changing solar fluxes. Mendillo et al. (2003) showed that the "M1" peak on Mars responds to solar flares in much the same way as the *E* region on Earth.

In their study of the Mars Express (MEX) radio occultation profiles, Pätzold et al. (2005) named the upper peak "M1", the lower peak "M2", and a sporadic peak that appears below 110 km "M3". The latter peak has been suggested to arise from meteoric ions, such as Fe^+, Mg^+, Si^+ and their oxides, which are formed either directly from ablation of meteors, or indirectly by photoionization and charge transfer to the ablated meteoric neutrals. On the inner planets, the latter two sources are the most important (e.g., Grebowsky et al., 2002). Withers et al. (2008) have investigated the occurrence of these lower layers in the MGS RSS profiles, and they have called the peaks "M_M".

1.2. Essentials of Chapman theory

Several attempts have been made to explain the behavior of the martian ionosphere within the framework of Chapman (1931a,b) theory or somewhat modified Chapman theory, including, for example, Lindal et al. (1979), Bauer and Hantsch (1989), Hantsch and Bauer (1990), Zhang et al. (1990), Kliore (1992), Breus et al. (1998), Rishbeth and Mendillo (2004), Martinis et al. (2003), Zou et al. (2005, 2006), Withers and Mendillo (2005), Nielsen et al. (2006), Morgan et al. (2008), and Withers (2009). Most of these studies are based on radio occultation profiles from various previous and current Mars missions, but recently there have been investigations that employ data from the MEX MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) instrument, which is a low frequency radar that operates by vertical sounding (e.g., Picardi et al., 1999; Gurnett et al., 2005, 2008). The ionograms produced by this instrument can be used to infer the altitude and magnitude of the F_1 electron peak and the shape of the topside electron density profile. Most of the investigations of both types have focused on the variation of the peak densities and altitudes as a function of SZA and/or solar activity. Some have used the shape of a narrow region around the main peak profiles to derive the neutral scale heights of the thermosphere (e.g., Bauer and Hantsch, 1989; Breus et al., 2004; Zou et al., 2005; Withers and Mendillo, 2005).

A full exposition of Chapman layer theory as it relates to ionospheres can be found in many standard text books including, for example, Bauer (1973), Banks and Kockarts (1973), Rishbeth and Garriott (1969), Chamberlain and Hunten (1987), Bauer and Lammer (2004), Prölss (2004), and Schunk and Nagy (2009). Here we present only a few key equations. In Chapman theory, ionization of a single molecular species XY is produced by monochromatic solar photons in an isothermal atmosphere, and a single positive ion is formed. The ion production rate at altitude z is given by the general expression $q^i(z) = F(z)\sigma^i n_{XY}(z)$, where $F(z)$ is the local monochromatic solar photon flux, σ^i is the photoionization cross section of the single species at a single wavelength, and $n_{XY}(z)$ is the number density of the single neutral constituent. The altitude dependence of the ion production rate as a function of SZA χ and altitude z can be expressed as

$$q^i_\chi(z) = q^i_{\max,0} \exp\left[1 - \frac{z}{H} - \sec\chi e^{-z/H}\right], \quad (1)$$

where $q^i_{\max,0}$ is the ionization rate for overhead Sun ($\chi = 0$), $H = kT/mg$ is the (assumed constant) scale height of the neutral atmosphere, m is the mass of the species XY, T is the (assumed constant) neutral temperature, and g is the (assumed constant) acceleration of gravity. We have simplified Eq. (1) by defining $z = 0$ as the altitude of the subsolar maximum ionization rate, which is found at unit optical depth; z is defined relative to this altitude. Other authors have replaced z with equivalent expressions, such as $(h - h_0)$ where h is the altitude, and h_0 is the altitude of the peak for $\chi = 0$.

Since photochemical equilibrium prevails in a Chapman layer, the altitude of ion production is assumed to be equal to the altitude of ion loss. It is not widely recognized that dissociative recombination (DR) was not a part of original Chapman theory. Chapman (1931a) assumed that the single ion could be atomic or molecular, and that the recombining negative particles could be either negative ions or electrons, or some combination thereof. A generic recombination rate coefficient of 2×10^{-10} cm^3 s^{-1} was assumed for the unknown recombination process or processes. During the following ∼15 years, investigators gradually realized that the measured ionospheric electron densities were not consistent with several of the possible recombination