Wright State University

CORE Scholar

Physics Faculty Publications

Physics

10-1-2004

Response of the Martian Thermosphere/Ionosphere to Enhanced Fluxes of Solar Soft X Rays

Jane L. Fox

Wright State University - Main Campus, jane.fox@wright.edu

Follow this and additional works at: <https://corescholar.libraries.wright.edu/physics>

Part of the [Physics Commons](#)

Repository Citation

Fox, J. L. (2004). Response of the Martian Thermosphere/Ionosphere to Enhanced Fluxes of Solar Soft X Rays. *Journal of Geophysical Research-Space Physics*, 109, A11310.
<https://corescholar.libraries.wright.edu/physics/23>

This Article is brought to you for free and open access by the Physics at CORE Scholar. It has been accepted for inclusion in Physics Faculty Publications by an authorized administrator of CORE Scholar. For more information, please contact library-corescholar@wright.edu.

Response of the Martian thermosphere/ionosphere to enhanced fluxes of solar soft X rays

J. L. Fox

Department of Physics, Wright State University, Dayton, Ohio, USA

Received 7 January 2004; revised 18 August 2004; accepted 3 September 2004; published 18 November 2004.

[1] We have investigated the response of the thermosphere and ionosphere of Mars to enhanced fluxes of solar soft X rays, such as those that have been detected by the SNOE satellite (e.g., *Bailey et al.*, 2000). We have constructed standard models by adopting the SC#21REFW and F79050N solar fluxes from H. E. Hinteregger (private communication) (see also *Torr et al.*, 1979) for the low and high solar activity models, respectively. We then constructed enhanced soft X-ray models by multiplying the solar photon fluxes for wavelengths below 200 Å by a factor of 3 at low solar activity and by a factor of 6 at high solar activity. We discuss the effects of the larger fluxes of soft X rays on the ion and electron density profiles and the minor neutral density profiles. We find that increasing the Hinteregger soft X-ray fluxes by a uniform factor below 200 Å cannot reproduce the distinct lower peaks that have been observed in some of the electron density profiles measured by the radio science experiment on the Mars Global Surveyor (MGS), and that were modeled previously by *Fox et al.* (1995) using the SERF2 solar fluxes of *Tobiska* (1991). In our model computations, the lower peak appears only as a shoulder, although the magnitude of the electron density at the shoulder is comparable to those exhibited by the MGS radio occultation profiles. This is in contrast to models of the terrestrial ionosphere, where increasing the solar fluxes by a uniform factor of 2–4 for wavelengths less than 250 Å has been found to bring the model electron and NO density profiles, and the shape of the photoelectron flux spectra, into agreement with the measured values.

INDEX TERMS: 5435 Planetology: Solid Surface Planets: Ionospheres (2459); 0343 Atmospheric Composition and Structure: Planetary atmospheres (5405, 5407, 5409, 5704, 5705, 5707); 2459

Ionosphere: Planetary ionospheres (5435, 5729, 6026, 6027, 6028); 5704 Planetology: Fluid Planets:

Atmospheres—composition and chemistry; **KEYWORDS:** Mars thermosphere, Mars ionosphere, soft X rays

Citation: Fox, J. L. (2004), Response of the Martian thermosphere/ionosphere to enhanced fluxes of solar soft X rays, *J. Geophys. Res.*, 109, A11310, doi:10.1029/2004JA010380.

1. Introduction

[2] That the solar soft X-ray fluxes were underestimated by the standard solar flux models of H. E. Hinteregger (private communication, 1980) [see also *Torr et al.*, 1979] has been suggested by several measurements and models. *Richards and Torr* [1984] modeled the photoelectron fluxes derived from the Atmospheric Explorer-E (AE-E) satellite [*Lee et al.*, 1980] at solar minimum and found that the shape of the suprathermal photoelectron flux spectra could be reproduced by doubling the solar fluxes of the Hinteregger F74113 spectrum below 250 Å. This was considered justifiable because the F74113 fluxes shortward of 250 Å were not measured on day 113 of 1974, but were derived from other measurements [*Heroux and Hinteregger*, 1978]. Both the F74113 and SC#21REF solar fluxes pertain to low solar activity conditions. *Richards et al.* [1994] proposed that the F74113 spectrum, which was based on measurements from a rocket flight [*Heroux and Higgins*, 1977],

better reflected low solar activity conditions than the SC#21REF spectrum, which was obtained from extrapolation of AE-E measurements from 1977 and 1980, a time of relatively high solar activity. The SC#21REF spectrum was normalized by utilizing solar flux data from a 1979 rocket flight [*Hinteregger et al.*, 1981]. The F74113 fluxes are about a factor of 2 larger than the SC#21REF fluxes below 300 Å. *Richards et al.* proposed that the fluxes of the SC#21REF spectrum for wavelengths less than 300 Å should be increased by up to a factor of 4 to reproduce the shape of the AE-E model photoelectron spectra.

[3] *Conway* [1984] modeled the AE-E dayglow spectrum in the 3300–3500 Å region. He found that by including the (0, 9) Vegard-Kaplan (VK) band at 3200 Å along with the (0, 0) N₂ second positive band at 3371 Å, the dayglow intensities measured by the AE-E filter photometer could be brought into agreement with the photoelectron theory of *Kopp et al.* [1977]. An analysis of the predicted and measured second positive dayglow intensities, however, indicated that the photoelectron fluxes measured by AE-E were too large by a factor of nearly two. Undoubtedly many parameters used in these older models have been updated.

Strickland *et al.* [1999] later showed by using their Atmospheric Ultraviolet Radiance Integrated Code (AURIC) that better agreement with the measured photoelectron fluxes could be obtained by increasing the Hinteregger solar fluxes for photons with wavelengths below 250 Å by a factor of 2.

[4] Ogawa and Judge [1986] used a rocket-borne Ne ionization chamber to measure the integrated solar flux between 50 and 575 Å, with an estimated error of 7.3%. Their results indicated that the Hinteregger fluxes in this wavelength region were low by a factor of 2 at low solar activity and by 30% at high solar activity. Because the wavelength range of the measurements extended well into the EUV, the amount of the underestimate due to soft X rays could not be determined.

[5] Barth *et al.* [1988; see also Barth, 1996] proposed that since the highly variable solar fluxes with wavelengths from 20 to 100 Å deposit their energy in the terrestrial altitude region where the NO densities are observed to maximize, the energetic photoelectrons produced by these soft X rays were responsible for the large magnitudes and variability in the low latitude NO densities observed by the Solar Mesosphere Explorer (SME) satellite. The SME ultraviolet spectrometer measured the NO densities through observations of the (1, 0) NO γ ($A^2\Sigma^+ \rightarrow X^2\Pi$) band at 2150 Å as a function of altitude and latitude over the period 1982 to 1986. The maximum densities at low latitudes were observed near 110 km. The large densities at high latitudes are assumed to be produced by auroral energetic (~ 1 – 10 keV) electron precipitation [e.g., Gérard and Barth, 1977; Gérard *et al.*, 1984; Barth *et al.*, 2003; Petrínek *et al.*, 2003]. Cleary [1986] developed a photochemical model of the NO densities in which variations in the EUV fluxes did not reproduce the observed low latitude NO density variations. The NO densities did, however, respond to larger variations in the soft X rays. Indeed, unit optical depth for wavelengths between 250 and 1000 Å in the terrestrial atmosphere is reached between 150 and 170 km, whereas soft X rays with wavelengths less than 150 Å are absorbed below 120 km, near the maximum of the nitric oxide density profile.

[6] The Student Nitric Oxide Explorer (SNOE) Solar X-ray Photometer (SXP) was designed to determine the soft X-ray fluxes using a series of photodiodes with thin film coatings rather than the less reliable foil filters [e.g., Bailey *et al.*, 1999a]. The measurements were reported as daily averages of X-ray fluxes in three channels (20–70 Å, 60–190 Å, and 170–200 Å) beginning in March 1998 [e.g., Bailey *et al.*, 2000]. The NO density profiles were obtained from limb scans of the fluorescent scattered emission from the (1, 0) and (0, 1) γ bands by the ultraviolet spectrometer. Barth *et al.* [1999] found a correlation between the magnitude of the soft X-ray fluxes and the densities of equatorial NO as returned by the first four months of SNOE data in mid-1998. For the period of the measurements, which was at moderate solar activity, they found that the Hinteregger models underpredicted the magnitude of the soft X-ray fluxes in all three channels. Bailey *et al.* [2000] reported the fluxes in the three wavelength channels for a range of $F_{10.7}$ from about 100 to 175, and showed that the photon fluxes increased over this range by factors of 8.3, 7.0, and 3.5 for the 20–70, 60–190, and 170–200 Å channels, respectively. Solomon *et al.* [2001] showed that increasing

the Hinteregger solar fluxes for moderate solar activity by a factor of 4 for wavelengths less than 250 Å brought their model profiles of the terrestrial electron density into agreement with the incoherent scatter profiles of Buonsanto *et al.* [1992, 1995]. The SNOE data showed also that the long-term variability in the solar soft X rays was larger than the Hinteregger solar spectra predicted [Bailey *et al.*, 2000].

[7] In the past, various investigators have identified different wavelength ranges as that for which the fluxes were underestimated in the Hinteregger spectra. Upper wavelength limits between 100 and 300 Å have been assumed [e.g., Barth *et al.*, 1988; Richards *et al.*, 1994; Strickland *et al.*, 1999; Bailey *et al.*, 1999b; Solomon *et al.*, 2001]. Solomon *et al.* [2001] described the wavelength range 10–300 Å as the “XUV” or hard extreme ultraviolet to soft X-ray region. In their ionosphere model, they increased the solar fluxes below 250 Å by a uniform factor of 4. We find that, if the solar photon fluxes with wavelengths up to 250–300 Å are increased, significant increases of the main F_1 peaks of both the Earth and Mars will be produced.

[8] Electron density profiles in the Martian ionosphere were returned from the radio science (RS) experiment on board the Mars Global Surveyor [e.g., Tyler *et al.*, 2001] (D. P. Hinson and the MGS Radio Science Team, Public access to MGS RS standard electron density profiles, available at <http://nova.stanford.edu/projects/mgs/eds-public.html>, 2003). A survey of these profiles shows the existence of a prominent E -region below the main F_1 peak. This feature sometimes appears as a shoulder and sometimes as a separate peak. We note here that the definition of the E and F_1 regions and peaks that we have adopted is based on the differences in the sources of the ions, and is the same as that used by Bauer [1973] and Banks and Kockarts [1977]. The F_1 peak is defined as arising from ionization by photons in the main part of the solar EUV spectrum, from about 250 to 910 Å. The E region is formed by ionization by soft X rays characterized by wavelengths less than 150, and by UV photons with wavelengths longer than 910 Å. On Earth, the latter source is more important than on Mars or Venus because O_2 , which is a major constituent in the terrestrial thermosphere, is ionized by solar Lyman β at 1026 Å. O_2 is only a minor constituent in the thermospheres of both Mars and Venus.

[9] The SERF2 solar spectra of Tobiska [1991] were characterized by a larger ratio of soft X ray to EUV photon fluxes than the Hinteregger (SERF1) fluxes [cf. Buonsanto *et al.*, 1992]. Fox *et al.* [1995] used the SERF2 fluxes to model the Martian thermosphere/ionosphere. These models (hereafter the SERF2 models) were the first models that showed a distinct lower peak in the Martian electron density profile. The SERF2 electron density profiles are shown in Figure 1, where they are compared to the Mariner 6 ingress radio occultation electron density profile [Fjeldbo *et al.*, 1970]. Only a shoulder appeared in models that were based on the Hinteregger solar fluxes. The magnitudes of the lower peaks in the Mariner 6 radio occultation electron density profiles were between those computed with the SERF2 solar fluxes and those computed with the Hinteregger solar fluxes.

[10] We have constructed updated standard and enhanced soft X-ray models for both low and high solar activities.

Figure 1. Electron density profiles for the low and high solar activity Hinteregger and SERF2 models. The larger densities are from the high solar activity models, and the smaller densities are from the low solar activity models. The solid curves are those from the SERF2 models, and the dotted curves were computed using the Hinteregger SC21REFW and F79050N spectra for low and high solar activities, respectively. The dashed curve is a smoothed electron density profile derived from the Mariner 6 radio occultation profiles [Fjeldbo *et al.*, 1970]. Taken from Fox *et al.* [1995].

For the solar fluxes in the wavelength range from 18 to 2000 Å, we have adopted the SC#21REFW and F79050N spectra from H. E. Hinteregger (private communication) [see also Torr *et al.*, 1979; Hinteregger *et al.*, 1981] for the low and high solar activity standard models, respectively. In the version we use, the photon fluxes are given as delta functions at the strong solar lines and at 1 Å intervals in the continuum from 18.62 to 2000 Å. We also include hard X rays in our model. The solar fluxes in the region $\lambda < 20$ Å are greatly affected by solar flares, these fluxes are known to be quite variable [e.g., Banks and Kockarts, 1977]. For the wavelength range 1–17 Å in the high solar activity standard model we have adopted the photon fluxes at 1 Å intervals that were obtained from Ayres [1997, also private communication, 1996], and we reduced those fluxes by a factor of 50 for low solar activity. The Yohkoh Soft X-ray Telescope (SXT) returned relative X-ray emissions for the wavelength range 3–37 Å; these data showed a variability of a factor of about 100 from low to high solar activity [Acton *et al.*, 1999]. In order to mimic this variation, for the high solar activity enhanced X-ray model we have increased the hard X-ray solar fluxes by a factor of 2. For the low solar activity enhanced X-ray model, we used the same 1–17 Å fluxes as the standard model. The variability of the fluxes in this wavelength region is so large that the adopted fluxes should only be considered as estimates. Furthermore, these photons are absorbed below 100 km in the D-region, which is below the region of interest here. We have assumed a solar zenith angle of 60° in all the models presented here, and an average heliocentric distance for Mars of 1.523 AU.

[11] The SNOE data suggested that the Hinteregger soft X-ray fluxes were underpredicted more at high than at low solar activity [Bailey *et al.*, 2000]. For the enhanced soft

X-ray models, (hereafter the enhanced X-ray models) the solar photon fluxes for wavelengths in the range 18 to 200 Å in our models were increased by factors of 3 and 6 at low and high solar activities, respectively. Bougher *et al.* [2001] increased the soft X-ray fluxes below 150 Å by a factor of 10 in their Mars Thermospheric General Circulation Model (MTGCM) to produce a lower peak in the electron density profiles that could be compared to those observed by the MGS. We investigate here the response of the thermosphere and ionosphere of Mars to enhanced fluxes of solar soft X rays, including ion production rates, ion and electron density profiles, and density profiles of the minor species NO, N(⁴S), N(²D), N(²P), and C.

2. Background Models

[12] The background models have been updated since 1995 and contain 12 species, as shown in Figure 2. Only H₂ has been added to the background atmosphere since 1995. As Fox [2001, 2003a] has shown, however, H₂ in abundances greater than 4 ppm has a significant effect on the O⁺, CO⁺, CO₂⁺, and N₂⁺ density profiles. The low solar activity model used here is based on the measurements of Viking [e.g., Nier and McElroy, 1976], and the high solar activity model is based on density profiles taken from the MTGCM of Bougher *et al.* [1990, 1999, 2000, also private communication, 2000]. The exospheric temperatures in the low and high solar activity models are 200 K and 300 K, respectively. The mixing ratio of O in the low solar activity model is 0.02 at 130 km, and was derived from the Viking Retarding Potential Analyzer (RPA) measurements of the O₂⁺ and CO₂⁺ profiles by Fox and Dalgarno [1979]. Values between 0.01 and 0.03 have been derived by other investigators [e.g., Nier *et al.*, 1976; Hanson *et al.*, 1977; Krasnopolsky, 2002]. At high

Figure 2. Background neutral density profiles for standard low and high solar activity models. The molecular and H density profiles are represented by solid curves; He and H₂ densities are represented by dotted curves; C, N, and NO density profiles are represented by dashed curves. The latter densities are computed self-consistently in the models, and the variations in these densities from the standard to enhanced X-ray models are presented in Figure 11 below. The H and H₂ density profiles also vary for the enhanced X-ray models, but these variations are not discussed here. (top) Standard low solar activity model (“Lo”). (bottom) Standard high solar activity model (“Hi”).

solar activity, the O density profile was taken from the MTGCM, and its abundance is approximately 0.017 at 130 km. Since O is produced by photolysis of CO₂, we might expect that, by analogy to Venus, the O abundances would be larger at high solar activity. It is possible that dynamical processes, including large scale winds and eddy diffusion, act to limit the mixing ratio variations over a solar cycle [e.g., Bougher *et al.*, 2000]. In addition, there is a lack of data on the O abundances at both low and high solar activities. We therefore chose not to change the O density profile in the MTGCM model. The resulting O mixing ratios at the *F*₁ peaks are similar for all the models, ranging from 0.027 to 0.029 near 136 km at low solar activity and from 0.025 to 0.027 near 138 km at high solar activity.

[13] We adopted an H₂ abundance at the lower boundary of 15 ppm, as derived by Krasnopolsky and Feldman [2001] from intensities of (6, 3) and (6, 1) bands of the H₂ Lyman ($B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$) band system, which they measured using the Far Ultraviolet Spectrometer Explorer (FUSE). The atomic hydrogen densities at the lower boundary were fixed so that the densities at 250 km were similar to those inferred from the models of Krasnopolsky and Feldman [2001], about $4 \times 10^5 \text{ cm}^{-3}$ at low solar activity and $3 \times 10^4 \text{ cm}^{-3}$ at high solar activity. The high solar activity value is consistent with that determined from analyses of the Lyman alpha emissions measured on the Mariner spacecraft [e.g., Anderson and Hord, 1971]. At the tops of the models, we imposed upward velocity boundary conditions on H and H₂. The upward velocities of H were reduced by a factor of 2 from the theoretical Jeans velocities, to account for suppression of the tail of the velocity distribution by the escaping atoms, as suggested by Shizgal and Blackmore [1986]. A helium abundance of 4 ppm [Krasnopolsky and Gladstone, 1996] was imposed at the lower boundaries of the models. The N, NO, and C profiles were computed self-consistently in the models.

[14] The set of photoabsorption and photoionization cross sections that we have adopted has undergone considerable revision since the 1995 SERF2 models were published. Among other changes, some of which were reported by Fox and Sung [2001], we have adopted the short wavelength cross sections from the calculations of Verner and Yakovlev [1995] for atoms. For molecules, the k-shell cross sections were assumed to be the sum of those for the constituent atoms. We adopted the theoretical cross sections from 1 Å to the shortest wavelength for which measured cross sections were available for each species. The photoabsorption cross sections for O in particular have been thoroughly revised since 1995, as described by Fox and Sung [2001].

[15] The photoelectron grid extends from 0 to 300 eV, in 1 eV intervals. Electrons produced with energies greater than 300 eV by the absorption of X rays, and auger electrons from k-shell ionization of O and C are included approximately, however, by dividing the energy of the electron in eV by 300, placing the appropriate number of electrons into the top energy bin, and by placing one electron into the bin which represents the remainder of the energy. Thus the energy of the all the photoelectrons is accounted for, but the primary electron production spectra have anomalous peaks, particularly at 300 eV.

[16] The full set of chemical reactions and rate coefficients in the Venus/Mars model was reported by Fox and Sung [2001]. Modifications to the rate coefficients since that compilation include that for the reaction

The 2003 JPL evaluation recommends the value $2.1 \times 10^{-11} \exp(100/T) \text{ cm}^3 \text{ s}^{-1}$ [DeMore *et al.*, 1994; Sander *et al.*, 2003], rather than the constant value of $3.4 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ recommended previously [Lee *et al.*, 1978; DeMore *et al.*, 1992]. The recommended values do not apply to the temperatures below 200 K, such as those in the Martian lower thermosphere. The measurements of Wennberg *et al.* [1994] indicate a slight negative temperature dependence down to temperatures of 220 K, but they

Table 1. Revised Transition Probabilities^a

Wavelength, Å	Transition,	A, s ⁻¹	Reference ^a
3728, 3726	O ⁺ (² D) → O ⁺ (⁴ S) + hν	8.88 × 10 ⁻⁵	Zeppen [1982]
7319, 7329	O ⁺ (² P) → O ⁺ (² D) + hν	1.733 × 10 ⁻¹	Zeppen [1982]
2470	O ⁺ (² P) → O ⁺ (⁴ S) + hν	4.53 × 10 ⁻²	Zeppen [1982]
5200	N(² D) → N(⁴ S) + hν	1.28 × 10 ⁻⁵	Butler and Zeppen [1984]
10,400	N(² P) → N(² D) + hν	8.0 × 10 ⁻²	Butler and Zeppen [1984]
3466	N(² P) → N(⁴ S) + hν	5.308 × 10 ⁻³	Butler and Zeppen [1984]
6300, 6364	O(¹ D) → O(³ P) + hν	7.445 × 10 ⁻³	Baluja and Zeppen [1988]
5577	O(¹ S) → O(¹ D) + hν	1.215	Baluja and Zeppen [1988]
2972	O(¹ S) → O(³ P) + hν	7.601 × 10 ⁻²	Baluja and Zeppen [1988]

^aAs collected by Swaminathan *et al.* [1998].

suggest that their measurements do not rule out some non-Arrhenius behavior. Subsequent calculations of the rate coefficient for this radical-radical reaction [e.g., *Duff and Sharma*, 1997; *Gamallo et al.*, 2003], however, support the measurements.

[17] The branching ratios of the products of O₂⁺ dissociative recombination

for the first two channels reported in *Fox and Sung* [2001] contain a slight error. The branching ratios for the channels that produce O(³P) + O(³P) and O(³P) + O(¹D) were given as 0.20 and 0.44, respectively, whereas those measured by *Kella et al.* [1997] were actually 0.22 and 0.42, respectively. *Peeverall et al.* [2001] more recently measured the branching ratios as a function of energy from 1 meV to 3 eV. They found the branching ratios to be highly energy-dependent, especially the yield of O(¹S) at thermal energies, which they found to be in the range 0.011 to 0.019. The *Kella et al.* [1997] O(¹S) yield was reported as 0.05 for dissociative recombination of ground state O₂⁺ and 0.09 for a vibrationally excited sample of O₂⁺. Because O₂⁺ is vibrationally excited at high altitudes [e.g., *Fox and Hać*, 1997], and because of uncertainties in the electron temperatures and the subsequent difficulties in applying the branching ratios of *Peeverall et al.* [2001], we have chosen to retain the branching ratios of *Kella et al.* [1997].

[18] The transition probabilities (Einstein A-factors) for the most important forbidden transitions of metastable excited states of O⁺, O, and N given by *Fox and Sung* [2001] have been superseded by the later calculations of *Zeppen* [1982], *Butler and Zeppen* [1984], and *Baluja and Zeppen* [1988], as pointed out by *Swaminathan et al.* [1998]. The more recent values are listed in Table 1.

[19] The ion density profiles were computed with zero-flux upper boundary conditions, and consequently the high altitude ion scale heights and densities are overestimated. Several investigators have shown that the major ion densities measured by the RPA on Viking [*Hanson et al.*, 1977] can only be reproduced in 1-D models by imposing upward velocity boundary conditions at the tops of the models [e.g., *Chen et al.*, 1978; *Shinagawa and Cravens*, 1989; *Fox*, 1993, 1997]. This upward flux represents a high altitude loss process for the ions, probably the divergence of the horizontal fluxes. *Fox* [1997] showed that the loss rates of ions are limited roughly by their production rates above the photochemical equilibrium region, and predicted that the ion with the largest loss rate would be O₂⁺. *Ma et al.* [2002;

see also *Liu et al.*, 2001] used multi-species MHD models of the ionosphere/solar wind interaction to show that ions are indeed transported at high altitudes across the terminator. The trans-terminator ion fluxes computed by *Ma et al.* are within the upper limits reported by *Fox* [1997], and the escape rates are roughly in agreement with values derived from the ASPERA instrument on the Phobos mission [e.g., *Lundin et al.*, 1989]. Most of the analyses of Phobos data, however, were based on the assumption that the major escaping ion was O⁺ [e.g., *Lundin et al.*, 1990; *Verigin et al.*, 1991; *Kallio et al.*, 1995; *Lichtenegger and Dubinin*, 1998; *Jin et al.*, 2001]. *Ma et al.* [2004] recently computed trans-terminator and escape fluxes of O⁺, O₂⁺, and CO₂⁺ for a new MHD model on a spherical grid with finer altitude resolution. The results of the calculations for several cases showed significantly smaller fluxes. We focus here, however, on the major F₁ and lower E-region peak electron densities, which are not expected to be affected by the upper boundary condition. All the high altitude ion densities reported here are expected to be too large, as are density peaks for ions that maximize at high altitudes, including O⁺, H⁺, He⁺, N₂⁺, and CO⁺.

3. Photoionization Rates

[20] The solar photoproduction rates of CO₂⁺, N₂⁺, CO⁺, NO⁺, O⁺, C⁺, and N⁺ are shown in Figures 3 and 4, for the low and high solar activity models, respectively. In the figures we present both the production rates for models computed with the standard Hinteregger solar fluxes, and those for the enhanced X-ray fluxes, which were described previously. In Table 2, we present summaries of the altitudes and magnitudes of the peaks of the photoionization rate profiles for seven ions. The main peaks in the production profiles are due mostly to absorption of the portion of the EUV from 250 to 910 Å. The major ion produced is CO₂⁺, and its production rate maximizes at ~136 km at low solar activity and ~139 km at high solar activity. When the soft X-ray fluxes are enhanced, the peak photoionization rates are located ~0.5–1 km lower in the ionosphere, and the peak photoproduction rate of CO₂⁺ increases by 5% at low solar activity, and by 14% at high solar activity.

[21] Most of the production profiles also exhibit lower shoulders in the ranges 106–109 and 112–115 km, for low and high solar activity models, respectively, which result from the absorption of soft X rays. When only a lower shoulder appears, the altitude of the lower peak is identified as that for which the difference between the production rates at successive altitudes is a minimum; thus the altitude of the shoulder usually is placed between two integer altitudes,

Figure 3. Altitude profiles of the production rates of seven ions by photoionization for the low solar activity models. (top) Standard model (“Lo”). (bottom) Enhanced X-ray model (“Lo X”).

and is somewhat uncertain because of the 1 km altitude grid size. This method was also used to locate the shoulders in the profiles for the electron-impact ionization rates and the steady state model ion densities. For example, when the soft X rays are enhanced, the CO_2^+ production rate profile exhibits a lower shoulder near 106.5 km with a magnitude that increases by a factor of ~ 3 at low solar activity; the shoulder appears near 112.5 km and increases by a factor of ~ 6 at high solar activity. These factors are essentially the same as those by which the soft X rays have been increased. That the photoionization rates near the main peak increase shows that photons with wavelengths below 200 Å are absorbed in this region as well.

[22] The photoproduction rate of ions is dominated by that of CO_2^+ from ~ 115 to 207 km and from ~ 116 to 244 km at low and high solar activities, respectively; at higher altitudes production of O^+ is more important. O becomes the dominant neutral above 195 and 225 km in our low and high solar activity models, respectively. The difference between the “cross-over” altitudes for the neutral densities and the ion production rates reflects the difference in the photoionization cross sections, which are larger for CO_2 than for O. CO_2 and O have similar ionization thresholds: 13.76 eV for CO_2 and 13.6 for O. Near the main peak in the O^+ photoproduction rate, which occurs in the range 133–135 km in the standard model, and 130–131 km in the enhanced X-ray model, the most important production

process is photodissociative ionization of CO_2 ; at higher altitudes direct ionization of O dominates. Thus the photoionization rate profile above the peak follows the density profile of CO_2 at lower altitudes and that of O at higher altitudes. The calculated production rate of O^+ from dissociative ionization of CO_2 exceeds production of CO_2^+ below ~ 116 km at low solar activity and below ~ 122 km at high solar activity.

[23] Figures 3 and 4 and Table 2 show that the photoionization rate profiles of NO^+ peak near 91 km at low solar activity, and near 95 km at high solar activity. Most of the photoionization near the peak is produced by the absorption of solar Lyman alpha photons near 1216 Å. The magnitudes of the production rates at these altitudes decrease slightly as the solar soft X rays are enhanced for both low and high solar activities. This reflects the small decrease in NO densities in this altitude range in the enhanced X-ray models. Although the larger fluxes of soft X rays increase the odd nitrogen densities in this altitude range as they do on the Earth, the increase on Mars is reflected in larger densities of atomic N rather than NO. As will be shown below, our model does not reproduce the Viking measured NO densities [e.g., Nier et al., 1976] in the 120–140 km region [cf. Fox, 1993, 1994]. There also is a secondary peak in the photo-production rate of NO^+ near 135 km at low solar activity and a prominent shoulder at high solar activity near 139–142 km. These features arise from photoionization of NO by solar

Figure 4. Altitude profiles of the production rates of seven ions by photoionization for the high solar activity models. (top) Standard model (“Hi”). (bottom) Enhanced X-ray model (“Hi X”).

Table 2. Peak Altitudes and Production Rates Due to Photoionization for the Low and High Solar Activity Standard and Enhanced X-Ray Models

Species	Altitude, km	Production Rate, $\text{cm}^{-3} \text{s}^{-1}$	Altitude, km	Production Rate, $\text{cm}^{-3} \text{s}^{-1}$	Ratio ^a
<i>Low Standard and Enhanced X-Ray Models</i>					
CO_2^+	136	1.35(3) ^b	135.5	1.42(3)	1.05
	116.5	5.6(0)	106.5	1.7(1)	3.0
N_2^+	139	3.7(1)	138.5	3.9(1)	1.05
	108.5	2.3(−1)	108.5	6.9(−1)	3.0
O^+	132	2.4(2)	130.0	3.5(2)	1.44
	108.5	1.8(1)	108.5	5.5(1)	3.0
CO^+	133.5	1.40(2)	131.5	1.76(2)	1.26
	108.5	5.4(0)	108.5	1.63(1)	3.0
C^+	131.5	1.07(2)	128.5	1.70(2)	1.6
	108.5	1.04(1)	108.5	3.1(1)	3.0
N^+	134	5.8(0)	132	8.0(0)	1.4
	108.5	2.4(−1)	108.5	7.2(−1)	3.0
NO^+	135	2.6(−1)	132	2.6(−1)	0.9
	91.5	9.3(−1)	91.5	7.9(−1)	0.9
<i>High Standard and Enhanced X-Ray Models</i>					
CO_2^+	139	3.3(3)	139	3.8(3)	1.14
	112.5	1.92(1)	112.5	1.15(2)	6.0
N_2^+	146.5	8.4(1)	146	9.3(1)	1.10
	113.5	8.0(−1)	113.5	4.8(1)	6.0
O^+	135.5	7.2(2)	132	1.50(2)	2.1
	113.5	5.7(1)	113.5	3.4(2)	6.0
CO^+	137	4.5(2)	134	7.1(2)	1.6
	113.5	1.7(1)	113.5	1.01(2)	6.0
C^+	135	3.3(2)	131	7.8(2)	2.4
	114.5	3.4(1)	114.5	2.0(2)	6.0
N^+	137.5	1.4(1)	132	2.6(1)	1.85
	114.5	2.7(0)	114.5	1.6(1)	6.0
NO^+	139.5	2.8(−1)	138.5	3.3(−1)	1.16
	95	8.8(0)	95	7.0(0)	0.8

^aRatio of peak production rates for the enhanced X-ray model to those of the standard model.

EUV photons. Ambient NO^+ is, however, produced mostly in chemical reactions, and the direct ionization of NO has little effect on the density profiles of NO^+ .

[24] Figures 3 and 4 also show the photoproduction rates as a function of altitude for CO^+ , C^+ , N_2^+ , and N^+ . The photoproduction rate profiles of all these species exhibit a main peak and a lower shoulder. For the enhanced soft X-ray models we compute slightly larger production rates at the main peak and significantly larger production rates near the lower shoulders. For example, when the solar soft X-ray spectrum is enhanced, the main peaks in the computed photoionization profiles of CO_2^+ and N_2^+ increase by only small factors of 1.05–1.06 at low solar activity, and by factors of 1.12–1.17 at high solar activity. These increases are relatively small because the only source for each of these ions is photoionization of the parent neutrals, and most of the photoproduction of CO_2^+ and N_2^+ is due to absorption of photons with wavelengths between 250 Å and the thresholds at 901 and 796 Å, respectively.

[25] The increases in the production rates when the soft X rays are enhanced are larger for ions with multiple sources, such as CO^+ , O^+ , C^+ , and N^+ ; the factors by which the peak photoionization rate increases are in the range 1.3–2.0. This can be understood because these ions are produced mainly by photodissociative ionization of CO_2 and N_2 near and

below the main peak. The threshold wavelengths for photo-dissociative ionization of CO_2 to produce CO^+ , C^+ , and O^+ , are 637, 404, and 651 Å, respectively. The threshold for production of N^+ from photodissociative ionization of N_2 is 510 Å. Thus the photoproduction rates of these fragment ions are more sensitive to increases in the short wavelength region of the spectrum. By contrast, the threshold wavelengths for direct photoionization of CO, O, C and N are longer: 885, 911, 1101, and 853 Å, respectively. The production rates of CO^+ , O^+ , N^+ , and C^+ by direct photoionization of the parent neutrals are very small near the peaks of the production profiles. Direct ionization of the parent neutrals is, however, important at high altitudes.

[26] As Table 2 shows, the factors by which the lower shoulders in all the production profiles increase are virtually the same as the factors by which the solar soft X-ray fluxes are assumed to increase. At low solar activity, the lower peaks in the photoproduction rate profiles of CO_2^+ , N_2^+ , O^+ , C^+ , and N^+ increase by factors of ~ 3.0 from the standard to the enhanced X-ray models; at high solar activity, the lower peaks in the production rates of these ions increase by factors of ~ 6.0 . This clearly demonstrates that the lower peaks in the photoionization profiles are produced by photons with wavelengths less than 200, although this does not constrain the upper wavelength limit of the enhanced solar fluxes, which may in fact be less than 200 Å.

4. Electron-Impact Production Rates

[27] The model electron-impact ionization production rates are shown as a function of altitude for CO_2^+ , O^+ , CO^+ , N_2^+ , C^+ , N^+ and NO^+ for the low and high solar activity models in Figures 5 and 6, respectively. The top panels show the production rates computed with the standard solar fluxes, and the bottom panels show those computed with enhanced X rays. The altitudes and magnitudes of the peak production rates by electron-impact are summarized in Table 3. We have found that EUV photons with wavelengths shorter than 200 Å penetrate to altitudes below 128 to 133 km in our 60° SZA models.

[28] The production of energetic photoelectrons is mostly controlled by photoionization of CO_2 . Therefore the lower shoulders in the production rates of all the ions by electron-impact increase by nearly the same factors as those by which the soft X rays are assumed to be enhanced, that is, factors of 3 and 6 for low and high solar activities, respectively, at altitudes of 110–112 km and 113–115 km, respectively. The main part of the EUV is absorbed near 136 km at low solar activity and near 139 km at high solar activity. The electron-impact production rates peak 6–8 km lower than the photoproduction peaks for both standard models. In the enhanced X-ray models, the peaks for electron-impact ionization are 9–17 km below those for photoionization. The altitude of peak production by electron impact is lower than that by photoionization because, in general, the higher energy soft X-ray photons penetrate further into the atmosphere. As is well known, absorption of soft X rays, unlike the major portion of the EUV, produces higher energy photoelectrons, double ionization of valence shell electrons, and k-shell (or inner shell) ionization. K-shell ionization can lead to the ejection of a very energetic auger electron in the subsequent reorganization of the atom. These high energy

Figure 5. Altitude profiles of the production rates by electron-impact ionization of seven ions for the low solar activity models. (top) Standard model (“Lo”). (bottom) Enhanced X-ray model (“Lo X”).

and auger electrons can carry out several ionizations before they are thermalized.

[29] The electron impact production rates of CO_2^+ and N_2^+ near the main peaks increase from the standard to the enhanced X-ray models by a factor of ~ 2 at low solar activity and by a factor of ~ 3.4 at high solar activity. The peak electron-impact production rates of species that are sensitive to higher energy electrons, such as O^+ , CO^+ , C^+ , and N^+ , would be expected to increase by larger factors. Indeed, as Table 3 shows, the predicted increases of maximum production from the standard to the enhanced X-ray models for these ions is in the range 2.6–2.9 at low solar activity, and in the range 4.6–6 at high solar activity.

[30] A more distinct lower peak or shoulder appears in the altitude profile of the electron-impact production rates for the enhanced soft X-ray models than for the standard models. Thus when the soft X-ray flux is enhanced, the ratio of the upper peak to lower shoulder is smaller. These ratios for production of CO_2^+ and N_2^+ by electron-impact ionization are in the range 2–3 for the standard models. For the enhanced X-ray models, the lower peak is relatively larger, with upper to lower peak ratios of 1.2–2.1.

[31] Because they arise from multiple sources and are more sensitive to higher energy electrons, the maxima in the electron impact production rate profiles of CO^+ , O^+ , C^+ and N^+ are broad, with smaller ratios of upper peaks to lower shoulders. For O^+ and N^+ , the upper peaks are comparable

to the lower peaks at low solar activity; for C^+ , the peaks converge into a single maximum at low altitudes, as do the O^+ and N^+ peaks at high solar activity.

[32] Near the main peak, a larger fraction of the ionization is produced by solar photons than by electron-impact ionization; the lower shoulder is dominated by electron-impact ionization. Because the photoproduction rates of O^+ , CO^+ , C^+ , and N^+ are more sensitive to shorter wavelength photons and to higher energy electrons, we expect the upper peaks in the photo- and electron impact production rates of these ions should appear lower in the thermosphere, where the higher energy photons penetrate. This is indeed what we find. Like the CO_2^+ production profiles, however, the upper peak is dominated by photoproduction and the lower peak or shoulder by electron-impact production.

5. Ion and Electron Density Profiles

[33] The computed density profiles for the electrons and for ions that peak at lower altitudes, including O_2^+ , CO_2^+ , and NO^+ , are presented in Figures 7 and 8 at low and high solar activities, respectively, for both the standard and enhanced soft X-ray models. Also shown are the density profiles for O^+ , which peak above 200 km. The altitudes and magnitudes of the E , F_1 , CO_2^+ , O_2^+ , and O^+ peaks are summarized in Table 4. The low solar activity profiles of O_2^+ , CO_2^+ , and O^+ are compared to the measured values from the Viking

Figure 6. Altitude profiles of the production rates by electron-impact ionization of seven ions for the high solar activity models. (top) Standard model (“Hi”). (bottom) Enhanced X-ray model (“Hi X”).

Table 3. Peak Production Rates and Altitudes Due to Electron Impact Ionization for the Low and High Solar Activity Standard and Enhanced X-Ray Models

Species	Altitude, km	Production Rate, $\text{cm}^{-3} \text{s}^{-1}$	Altitude, km	Production Rate, $\text{cm}^{-3} \text{s}^{-1}$	Ratio ^a
<i>Low Standard and Enhanced X-Ray Models</i>					
CO_2^+	132	$3.3(2)^b$	126	$6.5(2)$	2.0
	110.5	$1.19(2)$	110.5	$3.6(2)$	3.0
N_2^+	131	$8.8(0)$	128	$1.71(1)$	2.0
	110.5	$2.7(0)$	110.5	$8.1(0)$	3.0
O^+	125	$3.2(1)$	121.0	$8.5(1)$	2.7
	110.5	$2.6(1)$	110.5	$7.9(1)$	3.0
CO^+	125	$3.2(1)$	123.5	$8.3(1)$	2.6
	111.5	$1.95(1)$	110.5	$5.7(1)$	2.9
C^+	119	$1.18(1)$	118.5	$3.5(1)$	2.9
	110.5	$1.17(1)$	110.5	$3.5(1)$	3.0
N^+	124	$8.5(-1)$	122.5	$2.4(0)$	2.8
	111.5	$7.1(-1)$	111.5	$2.1(0)$	3.0
NO^+	138	$1.41(-2)$	137.5	$2.2(-2)$	1.6
	109.5	$3.9(-4)$	109.5	$1.10(-3)$	2.8
<i>High Standard and Enhanced X-Ray Models</i>					
CO_2^+	132.5	$1.03(3)$	128	$3.4(3)$	3.3
	116.5	$4.5(2)$	115	$2.7(3)$	6.0
N_2^+	134.5	$2.1(1)$	128	$7.4(1)$	3.5
	116.5	$1.0(1)$	115.5	$6.0(1)$	6.0
O^+	115	$1.03(2)$	114	$6.2(2)$	6.1
CO^+	130.5	$1.08(2)$	126.5	$4.9(2)$	4.6
	116.5	$7.2(1)$	115.5	$4.3(2)$	6.0
C^+	114	$4.7(1)$	114	$2.8(2)$	6.0
N^+	114	$2.7(0)$	114	$1.6(1)$	6.0
NO^+	144	$1.64(-2)$	139	$4.1(-2)$	2.5
	114.5	$2.7(-3)$	115.5	$1.58(-2)$	5.8

^aRatio of peak production rates for the enhanced X-ray model to those of the standard model.

^bRead as 3.3×10^2 .

Retarding Potential Analyzer [Hanson *et al.*, 1977]. The high solar activity electron density profiles are compared with the Mariner 6 ingress profiles [Fjeldbo *et al.*, 1970]. As explained previously, owing to the zero flux upper boundary conditions, the high altitude ion densities should be considered as upper limits. The photochemical equilibrium boundary of O^+ is near its peak density, which is located at ~ 220 km at low solar activity and at ~ 255 km at high solar activity. Vertically or horizontally flowing O^+ ions will reduce the computed densities at and above the peaks. This study is focused on the region near the electron density peaks, which are found below 145 km, and relative densities at high altitudes are more accurate than the absolute values.

[34] The F_1 peak for both standard and enhanced soft X-ray models is found in the range 136–137 km at low solar activity, and from 137–139 km at high solar activity. Both the low and high solar activity models also show a lower shoulder below the major n_e peak, which appears near 110 km at low solar activity and near 115 km at high solar activity and is identified as the E -region peak. The F_1 peak appears lower in the ionosphere for both enhanced X-ray models. The fraction of ionization due to soft X rays and their associated high energy photoelectrons is larger in these models, thus moving the altitude of the maximum density to lower altitudes. The effect is more pronounced at high solar activity because the soft X rays were increased by a larger factor at high solar activity than those at low solar activity.

[35] The F_1 electron density peaks at low solar activity are about 8.7×10^4 and $9.5 \times 10^4 \text{ cm}^{-3}$, for the standard

and enhanced soft X-ray models, respectively. The analogous values at high solar activity are 1.6×10^5 and $2.0 \times 10^5 \text{ cm}^{-3}$, respectively. This represents an increase of only 10% for the low solar activity model, but a larger 25% increase at high solar activity. At low solar activity, the E -region peak electron density increases by a factor of 1.8, from 2.4×10^4 to $4.3 \times 10^4 \text{ cm}^{-3}$; at high solar activity, it increases by a factor of about 2.5, from 4.7×10^4 to $1.18 \times 10^5 \text{ cm}^{-3}$, from the standard to enhanced X-ray models. As expected from Chapman [1931] theory, these factors are approximately equal to the square roots of 3 and 6, the factors by which the soft X-ray fluxes are increased.

[36] The O^+ profile exhibits peaks near 219 km and 245–256 km at low and high solar activities, respectively. O^+ does not produce a visible F_2 peak on Mars because the O^+ density is at all altitudes less than that of the major ion O_2^+ . The O^+ peak densities for the standard and enhanced X-ray

Figure 7. Altitude profiles of the steady state number densities of electrons and four major ions: O_2^+ , CO_2^+ , O^+ , and NO^+ for the low solar activity standard and enhanced X-ray models. The measured densities from Viking 1 of O_2^+ , CO_2^+ , and O^+ are shown as solid squares, triangles, and circles, respectively [Hanson *et al.*, 1977]. (top) Standard low solar activity model (“Lo”). (bottom) Enhanced X-ray model (“Lo X”).

Figure 8. Altitude profiles of the steady state number densities of electrons and four major ions: O_2^+ , CO_2^+ , O^+ , and NO^+ for the high solar activity standard and enhanced X-ray models. The electron density profiles are compared to the Mariner 6 ingress profile, which is represented as a long-dashed curve. (top) Standard high solar activity model (“Hi”). (bottom) Enhanced X-ray model (“Hi X”).

models are 4.3×10^2 and $5.0 \times 10^2 \text{ cm}^{-3}$, respectively at low solar activity, and 1.47×10^3 and $1.9 \times 10^3 \text{ cm}^{-3}$, respectively, at high solar activity. With enhanced soft X-ray fluxes, the peak densities increase by $\sim 15\text{--}30\%$.

[37] Because the models pertained to solar zenith angles of 60° , and to the average sun-Mars distance of 1.52 AU, only a rough comparison to the densities derived from the Viking RPA data is appropriate [Hanson *et al.*, 1977]. Viking 1 entered the Martian atmosphere at a solar zenith angle of 44° , and at a heliocentric distance of 1.648 AU. In addition, the exospheric temperature (T_∞) is about 200 K in our low solar activity model, whereas the Viking exospheric temperature appears to be somewhat less. The temperatures derived from the Viking 1 and 2 landers show wave-like structure that makes identification of T_∞ difficult [Nier and McElroy, 1977]. The overall effect is that peaks in the photoionization production rate profiles in our low solar activity models should be slightly smaller and occur slightly

higher in the atmosphere than those for models based on the conditions of Viking. At altitudes where the solar fluxes are optically thin, such as near the O^+ peak, the production rates for different solar zenith angles should be roughly equal. Although the noise in the Viking 1 measured O^+ density profile is about 20%, the magnitude of the measured O^+ peak density is $\sim 7.5 \times 10^2 \text{ cm}^{-3}$, which is larger by $\sim 70\%$, and $\sim 50\%$ than those of the low solar activity standard and enhanced X-ray models, respectively. Thus, enhancing the soft X-ray flux appears to increase the O^+ densities somewhat. Although Fox [1993] reproduced the Viking peak value of O^+ in a model that included upward velocity boundary conditions for the ions, the neutral model was based on measurements of the Viking neutral mass spectrometer [e.g., Nier and McElroy, 1976, 1977], and the model contained no H_2 . H_2 destroys O^+ in the reaction

As stated above, we have assumed here that the H_2 mixing ratio is 15 ppm, as derived by Krasnopolsky and Feldman [2001]. Fox [2001, 2003a] showed that, owing to similar reactions with H_2 , the density profiles of O^+ , CO_2^+ , N_2^+ , and CO^+ are greatly affected by the assumed mixing ratio of H_2 for abundances greater than about 4 ppm. The Mars ionosphere model of Fox and Bakalian [2001] was constructed with a mixing ratio of 40 ppm H_2 , which was the previously accepted value that was based on the Mars Lyman alpha measurements of Krasnopolsky *et al.* [1998]. The O^+ peak in the density profile in this model, $\sim 300 \text{ cm}^{-3}$, was in serious disagreement with the Viking measured value.

[38] The peak densities and altitudes of O^+ , N_2^+ , and CO^+ decrease significantly as the H_2 mixing ratio increases. Since the density of CO_2^+ peaks at low altitudes, it is not much affected by the H_2 mixing ratio; reaction with H_2 is a major loss process for CO_2^+ principally at high altitudes. A smaller mixing ratio of H_2 or a larger O abundance could bring the model O^+ density profiles into better agreement with the Viking measured values [Fox, 2001, 2003a]. There is, however, no other evidence for a larger O abundance at low solar activity. In fact, Stewart *et al.* [1992] derived an even lower O abundance of $\sim 0.7\%$ at the ion peak from an

Table 4. Effect of Enhanced Soft X Rays on Peak Ion Densities^a

Peak	Altitude, km	Standard X Rays	Enhanced ^b X Rays	Ratio
<i>Low Solar Activity</i>				
O^+	219–220	4.3×10^2	5.0×10^2	1.16
O_2^+	135–136	7.6×10^4	8.3×10^4	1.10
CO_2^+	140–141	1.11×10^4	1.23×10^4	1.11
E	109–110	2.4×10^4	4.3×10^4	1.79
F_1	135–137	8.7×10^4	9.5×10^4	1.10
<i>High Solar Activity</i>				
O^+	255–256	1.47×10^3	1.91×10^3	1.30
O_2^+	135–139	1.36×10^5	1.70×10^5	1.25
CO_2^+	145–147	2.5×10^4	3.2×10^4	1.28
E	114–115	4.7×10^4	1.18×10^5	2.5
F_1	137–139	1.6×10^5	2.0×10^5	1.25

^aUnits are in cm^{-3} .

^bPhoton fluxes with wavelengths between 18 and 200 Å multiplied by a factor of 3 at low solar activity and by a factor of 6 at high solar activity.

analysis of the intensities at 1304 Å made by the Mariner 9 ultraviolet spectrometer. The considerable discrepancy between these measurements and those derived from the Viking measured ion density profiles has not been addressed. As mentioned previously, it has been suggested that winds and eddy diffusion may act to limit the variations of the thermospheric mixing ratio of O over a solar cycle [Bougher *et al.*, 2000].

[39] The O_2^+ profiles show that the density peak is considerably broadened and both the upper peak and lower shoulder, and the region between them are larger for the enhanced X-ray models. As Table 4 shows, that for low solar activity, the O_2^+ density at the upper peaks increase by $\sim 10\%$ from 7.6×10^4 to $8.3 \times 10^4 \text{ cm}^{-3}$ at 136 and 135 km, from the standard to the enhanced X-ray models. The Viking RPA placed the maximum density of O_2^+ near 130 km, with a magnitude of $9.0 \times 10^4 \text{ cm}^{-3}$ [Hanson *et al.*, 1977]. Chapman theory shows that as the solar zenith angle increases, the altitude of the molecular ion peaks also rise. We find that as the solar zenith angle changes from the Viking value of 44° to the 60° of our standard model, the O_2^+ density maxima should decrease by a factor of about 1.2 to $7.5 \times 10^4 \text{ cm}^{-3}$, and the altitude of the peak should rise by about 3 km. If the model value for T_∞ of about 200 K were decreased to about 180 K, the ion peak should appear somewhat lower also. Thus, although the peak in the Viking O_2^+ altitude profile is ~ 5 km lower than that of our model, when the differences in and uncertainties of the model are taken into account, the altitude and magnitude of the adjusted Viking peak density compares favorably with that of the low solar activity standard model. The discrepancy with the Viking model is larger for the enhanced X-ray model.

[40] The computed CO_2^+ main peak densities are $1.11 \times 10^4 \text{ cm}^{-3}$ at 141 km and $1.23 \times 10^4 \text{ cm}^{-3}$ at 140 km for the low solar activity standard and enhanced soft X-ray models, respectively. The CO_2^+ densities reported by Viking maximize in the range 134 to 139 km, with a value of about $1.3 \times 10^4 \text{ cm}^{-3}$. When the larger solar zenith angles assumed in the model compared to that of Viking is taken into account, this density is in acceptable agreement with that of the standard low solar activity model, but is slightly too large in the enhanced X-ray model. The difference between the standard and enhanced X-ray model CO_2^+ density peaks is, however, only about 12%, and is within the uncertainties of the measurements and models.

[41] Since O_2^+ is the major molecular ion and it is destroyed mostly by dissociative recombination, the O_2^+ density peaks near the altitude of maximum ion production, as Chapman theory would predict. CO_2^+ , however, peaks 5–8 km higher in the atmosphere because it is destroyed preferentially by reaction with O:

and

rather than by dissociative recombination. As stated previously, the mixing ratio of O at low solar activity has been assumed to be 0.02 at 130 km. Larger O abundances

would decrease the density of CO_2^+ relative to that of O_2^+ , and raise the altitude of the CO_2^+ peak. If in situ density profiles, preferably measured by an ion mass spectrometer, were available, the altitude difference between the O_2^+ and CO_2^+ peaks, in addition to the relative densities, could be used to infer the O abundances.

[42] At high solar activity, the peak CO_2^+ densities are 2.5×10^4 at 147 km, and $3.2 \times 10^4 \text{ cm}^{-3}$ at 145 km, for the standard and enhanced X-ray models, respectively. This increase by a factor of 1.3, like that of O_2^+ , is larger than that at low solar activity, due to the larger factor by which the solar fluxes below 200 Å are assumed to increase in the high solar activity model. The lower shoulder in the CO_2^+ density profiles appears near 110 km at low solar activity and near 116 km at high solar activity. When the soft X rays are enhanced in the low solar activity model, the magnitude of the lower peak increases by a factor of about 3. At high solar activity, the lower peak density increases by a factor of 5.7. Unlike the lower shoulders in the O_2^+ and electron density profiles, which increase by approximately the square root of the factor by which the soft X-ray photon fluxes are assumed to increase, these increases are approximately linearly proportional to this factor. Thus if in situ measurements of CO_2^+ densities near the lower peaks were available, they could be used as an independent indicator of the magnitude of the soft X rays. Remote sensing measurements of CO_2^+ are difficult. The major emissions of CO_2^+ in the ultraviolet are the $A^2\Pi_u \rightarrow X^2\Pi_g$ Fox-Duffendack-Barker bands, and the $B^2\Sigma_u^+ \rightarrow X^2\Pi_g$ ultraviolet doublet. These emissions are produced mainly in photoionization and electron impact ionization of CO_2 , and thus are not indicative of the ambient densities of CO_2^+ [cf. Fox, 1992]. Only the production rate due to fluorescent scattering by CO_2^+ is sensitive to the absolute CO_2^+ densities. Very little of either feature is produced by this source, and the existing limb profiles of the intensities from the Mariner ultraviolet spectrometer went off-scale at altitudes above the peak [e.g., Stewart, 1972]. Mixing of the CO_2^+ A and B states prior to radiation makes interpretation of the spectra even more difficult. There are infrared emission features of CO_2^+ at 500, 1283, and 1469 cm^{-1} (R. Sharma, private communication, 2004) [see also Gauyacq *et al.*, 1979]. If any of these emissions arising from the Martian lower thermosphere were detectable either from the ground or from orbiting spacecraft, the magnitude of the soft X-ray variability could be better constrained. Although all the ions exhibit lower shoulders, none of the other ion densities at these low altitudes is predicted to be large enough to be measurable.

[43] The NO^+ density profile exhibits only one peak in the range 94–95 km at low solar activity and at 98–100 km at high solar activity, although there is a hint of a lower shoulder about 5 km below the main peak. For both models, the NO^+ peak densities increase by approximately 20% from the standard to the enhanced X-ray models. NO^+ becomes the major ion just below the density peaks. Since NO is a minor constituent of the Martian atmosphere, chemical reactions rather than direct ionization of NO determine its density profile. Furthermore, since NO has the lowest ionization potential of all the species in the model, in regions where there are a sufficient number of

Figure 9. Altitude profiles of the steady state number densities of eleven ions: O_2^+ , CO_2^+ , NO^+ , O^+ , N_2^+ , CO^+ , C^+ , Ar^+ , N^+ , H^+ , and He^+ for the low solar activity standard and enhanced X-ray models. The densities of $O^+(^2D)$, $O^+(^2P)$, and O^{++} were computed, but are not shown in this figure. The O^+ profile is the sum of the densities of the ground and metastable states. The O^+ densities measured by the Viking RPA are represented by the long dashed curve and are shown for comparison [Hanson et al., 1977]. (top) Standard model (“Lo”). (bottom) Enhanced X-ray model (“Lo X”).

collisions, almost all ionization produces NO^+ eventually. Near its peak the major production reaction of NO^+ is

if its rate coefficient is near the upper limit of $1 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$. Otherwise the most important reaction is [Ferguson, 1973]

which has been found to proceed at nearly gas kinetic rates.

[44] The ion density profiles for all the ions from 80 to 300 km are shown in Figures 9 and 10 for the standard

and enhanced X-ray models at low and high solar activity, respectively. As has been found previously for Venus and Mars, and as these figures demonstrate, the composition of the ionosphere changes from low to high solar activity, with the densities of atomic ions increasing relative to molecular ions [cf. Fox and Sung, 2001; Fox et al., 1995].

[45] The C^+ and N^+ density profiles both peak at altitudes above 240 km, where our models, with zero-flux upper boundary conditions, predict more accurate relative densities than absolute values. The peak densities increase by factors of about 1.35 to 1.65 from the standard to enhanced soft X-ray models. The increases from low to high solar activity are factors of 3.2–5.5 for C^+ and 3.2–3.9 for N^+ [cf. Fox et al., 1995]. The C^+ density profiles exhibit broad, flat regions between 140 and 200 km in all the models. Just as for Venus, this structure appears because C^+ is produced

Figure 10. Altitude profiles of the steady state number densities of eleven ions: O_2^+ , CO_2^+ , NO^+ , O^+ , N_2^+ , CO^+ , C^+ , Ar^+ , N^+ , H^+ , and He^+ for the high solar activity standard and enhanced X-ray models. The densities of $O^+(^2D)$, $O^+(^2P)$, and O^{++} were computed, but are not shown in this figure. The O^+ profile is the sum of the densities of the ground and metastable states. (top) Standard model (“Hi”). (bottom) Enhanced X-ray model (“Hi X”).

Figure 11. Altitude profiles of the steady state number densities of the minor neutral species $N(^4S)$, $N(^2D)$, NO, and C for the low and high solar activity standard and enhanced X-ray models. The number densities for the standard model are given as solid curves; those for the enhanced X-ray models are given as dashed (N and NO) or dotted curves (C). The sum of the N and NO densities are also shown as dotted curves. The NO densities measured by Viking 1 are shown as open squares [Nier and McElroy, 1977]. (top) Low solar activity (“Lo SA”). (bottom) High solar activity (“Hi SA”).

near and below the peak by dissociative ionization of CO_2 and lost by reaction with CO_2 :

[cf. Dalgarno and Fox, 1994; Fox et al., 1995; Fox and Sung, 2001]. If the C^+ densities were in photochemical equilibrium (PCE) and the atmosphere were optically thin to ionizing radiation, the C^+ density would be nearly constant. At high altitudes, the PCE approximation begins to fail, and near and below the F_1 peak, the atmosphere is no longer optically thin, so the C^+ density decreases rapidly at low and high altitudes.

[46] Similarly, the predicted CO^+ profiles are also broad and flat between 160 and 200 km. This is because the major

production process for CO^+ is dissociative ionization of CO_2 , with some contribution from the reaction of C^+ with CO_2 , and the major loss process is reaction of CO^+ with CO_2 . Just as for C^+ , if PCE prevailed and the thermosphere were optically thin to ionizing radiation, the CO^+ density would be nearly constant. At low solar activity, the CO^+ peak density is near 209 km, and it increases by $\sim 20\%$ from the standard to the enhanced X-ray model. The high solar activity peak occurs near 248 km, and the increase from the standard to the enhanced X-ray model is $\sim 30\%$. The factor by which the peak density increases from low to high solar activity is in the range 6.3–6.9.

6. Minor Neutral Density Profiles

[47] Results from the SNOE spacecraft showed that the absorption of enhanced fluxes of soft X rays increased the terrestrial low latitude NO densities, bringing them into substantial agreement with the measured values [e.g., Barth et al., 1999]. We here examine the effects of enhanced X rays on the density profiles of the odd nitrogen species NO, $N(^4S)$, $N(^2D)$, and $N(^2P)$, and the minor species atomic C in the thermosphere of Mars. Zero flux lower boundary conditions were adopted for C, and downward fluxes for NO and N. For the metastable species $N(^2D)$ and $N(^2P)$, photochemical equilibrium was assumed at the lower boundary of the model. At the upper boundaries, diffusive equilibrium was assumed. The flux of NO at the lower boundary was taken somewhat arbitrarily to be $-2 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ at low solar activity and $-5 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ at high solar activity. The flux of N was taken to be $-1.0 \times 10^2 \text{ cm}^{-2} \text{ s}^{-1}$ at low solar activity and $-1.25 \times 10^2 \text{ cm}^{-2} \text{ s}^{-1}$ at high solar activity. Both of these fluxes represent downward velocities that are less than the approximate upper limit of K/H, where K is the eddy diffusion coefficient and H is the scale height of the atmosphere, but the fluxes were also constrained by the requirement that the computed densities be positive. No fine tuning was done. Models of the martian middle atmosphere have shown that the thermosphere is a source of N and NO to the middle atmosphere [e.g., Krasnopolsky, 1993]. Because, however, we have not modeled the middle atmosphere, the density profiles of odd nitrogen species should not be considered accurate below ~ 90 km, which is about 1.5 scale heights above the lower boundary.

[48] Figure 11 shows the computed low and high solar activity density profiles of these species. The solid curves are the density profiles for the standard models, and the dashed curves are those for the enhanced soft X-ray models. The NO densities measured by the Mass Spectrometer on Viking 1, as reported by Nier and McElroy [1977], are shown in the top panel of Figure 11 as open squares. It is clear that the larger soft X-ray fluxes make little difference for the NO density profiles, but the N density peaks are larger by 23% and 65% when the soft X-ray fluxes are enhanced at low and high solar activities, respectively. For the enhanced X-ray models, the computed peak densities of N are $2.9 \times 10^6 \text{ cm}^{-3}$ at 126 km at low solar activity, and $3.9 \times 10^6 \text{ cm}^{-3}$ at 111 km at high solar activity. NO is produced in the lower thermosphere by the reaction

and by the analogous reaction of ground state N

if the rate coefficient is close to the value $1 \times 10^{-16} \text{ cm}^3 \text{ s}^{-1}$, which we have assumed. As discussed by *Fox and Sung* [2001], only upper limits to the rate coefficients for reaction (10) of about $1.7 \times 10^{-16} \text{ cm}^3 \text{ s}^{-1}$, are available [cf. *Brown and Winkler*, 1970; *Herron and Huie*, 1968]. The rates of both of these NO production reactions increase in the lower thermosphere when the X rays are enhanced. The rates of the major loss processes for NO, reaction with N, (reaction (1)), and reaction with O_2^+

however, also increase. Thus while the production rates of NO are enhanced as the soft X-ray fluxes increase, the loss rates also increase, and the densities of NO are relatively insensitive to the soft X-ray fluxes in the model.

[49] When the soft X rays are enhanced, the peak densities of C increase by 11–18%, and those of $\text{N}(^2D)$ by 5–11%, where the larger values are for the high solar activity models. Although Figure 11 does not show the $\text{N}(^2P)$ density profiles, the peak densities are predicted to be $330\text{--}350 \text{ cm}^{-3}$ near 143 km, and $820\text{--}940 \text{ cm}^{-3}$ near 153 km, for the low and high solar activity models, respectively.

[50] There is a long-standing discrepancy in the low solar activity model NO densities and those from Viking 1 in the thermosphere from about 115 to 150 km [*Nier and McElroy*, 1976, 1977; *McElroy et al.*, 1976]. NO densities of about $3 \times 10^6 \text{ cm}^{-3}$ were measured near 135 km, whereas our model values at that altitude are about $1 \times 10^6 \text{ cm}^{-3}$ at low solar activity, with little variation from the standard to enhanced X-ray models. Thus the densities are underestimated when compared with the Viking measurements, but unlike NO in the terrestrial lower thermosphere, the discrepancy cannot be removed by enhancing the soft X rays in the Hinteregger solar spectra. As discussed earlier, the rate coefficient for the reaction of N with NO that we have adopted actually has a slight negative temperature dependence, while the previously recommended value was temperature-independent. *Fox* [1994] obtained agreement with the Viking NO densities by adopting a rate coefficient for this reaction with a large positive temperature dependences at the low temperatures of the Martian lower thermosphere, which fall in the range 100–200 K. Such large temperature dependences have been ruled out by recent measurements and calculations. The discrepancy between the measured and model NO densities is therefore actually larger here than in previous models.

[51] Except for the lowest point near 117 km, the Viking and model NO densities could be brought into agreement if the Viking mass spectrometer actually measured the sum of the N and NO densities. This could happen if N and O recombined inside the instrument. At 135 km, the N density is $(2.2\text{--}2.6) \times 10^6 \text{ cm}^{-3}$, where the range is from the standard low solar activity to the enhanced X-ray model. Thus the sum of the N and NO densities, about $(3.2\text{--}3.6) \times 10^6 \text{ cm}^{-3}$, is in good agreement with the NO densities

measured by Viking 1. Although the Viking landers carried open-source Nier-type mass spectrometers, neither O nor N densities could be measured in the Martian lower thermosphere. The O densities derived from the O_2^+ and CO_2^+ density profiles were substantial and our model density profiles of N are greater than those of NO. The large measured NO density at 117 km shown in Figure 11, however, militates against this interpretation.

[52] As *Nier and McElroy* [1977] show, however, the peak at mass-30 in the Viking mass spectrum is about half due to $^{12}\text{C}^{18}\text{O}$ and half due to NO. The accuracy of the derived NO densities therefore depends on the accuracy with which the $^{12}\text{C}^{18}\text{O}$ contribution can be determined. In addition, the Viking mass spectrometers were not calibrated in the laboratory for NO. In determining the densities, the electron impact ionization cross section for NO at 75 eV was assumed to be 80% of that for N_2 . Recent measurements of the N_2 and NO electron-impact ionization cross sections by *Straub et al.* [1996] and by *Lindsay et al.* [2000], respectively, show that the cross sections for production of the ions N_2^+ and NO^+ from their parent neutrals are actually comparable. The reported values for the cross sections for production of N_2^+ and NO^+ by impact of 75 eV electrons are about 1.90×10^{-16} and $1.94 \times 10^{-16} \text{ cm}^2$, respectively. Thus there are several reasons to believe that the NO densities reported by Viking may not be accurate.

7. Discussion

[53] Unlike the SERF2 Martian model ionospheres constructed by *Fox et al.* [1995], in which distinct lower peaks appeared near 100–105 km in the profiles for the electron density and the O_2^+ density, in these enhanced X-ray models, only lower shoulders appear. No obvious minimum between the upper peak and the lower peak is apparent, although the lower shoulder is more prominent at high solar activity than at low. Some of the differences can be ascribed to the use of different models, and some to the use of updated cross sections. One change has been to replace the short wavelength photoionization cross sections with those of *Verner and Yakovlev* [1995], rather than those from earlier calculations [*Weisheit*, 1974; *Daltabuit and Cox*, 1972], or earlier compilations [*Kirby et al.*, 1979]. The O photoionization cross sections from threshold to 1 Å were thoroughly updated in 1998. Other photoionization cross sections have been updated in other wavelength ranges [e.g., *Fox and Sung*, 2001], but all were updated in the short wavelength range. Finally, the SERF2 solar flux spectra of *Tobiska* [1991] contained significantly larger fluxes of soft X rays than the Hinteregger spectra.

[54] We find that the predicted F_1 peaks in the n_e profile for the SERF2 models are almost the same as those in our standard models. The enhanced X-ray models exhibit larger F_1 peaks than do those of the SERF2 models. For example, in the high solar activity models the F_1 peak increases from 1.6×10^5 to $2 \times 10^5 \text{ cm}^{-3}$ when the soft X rays are enhanced, compared to the SERF2 model upper peak density of $1.7 \times 10^5 \text{ cm}^{-3}$. The latter value and that of our standard high solar activity model value are in substantial agreement with the Mariner 6 radio occultation measurement [*Fjeldbo et al.*, 1970], although Mars was closer to the sun at that time than the average that we have assumed

Figure 12. Altitude for which the optical depth is unity for photons with wavelengths of 1 to 300 Å. The solid curves are for a solar zenith angle of 0° and the dashed curves are for a solar zenith angle of 60° . (top) High solar activity standard model (“High”). (bottom) Low solar activity standard model (“Low”).

here. For the low solar activity models, the F_1 peak density increases from 8.7×10^4 to $9.6 \times 10^4 \text{ cm}^{-3}$ when the soft X-ray fluxes are enhanced, while that of the SERF2 model is about $9 \times 10^4 \text{ cm}^{-3}$. These comparisons also indicate that our ion production rates near the F_1 peak may be too large in the enhanced X-ray models.

[55] The E-region n_e peak in the low solar activity SERF2 model, about $3 \times 10^4 \text{ cm}^{-3}$ was between those of the

standard and enhanced X-ray models: 2.6×10^4 and $4.4 \times 10^4 \text{ cm}^{-3}$, respectively, but again was closer to that of the standard model. At high solar activity, the lower peak in the electron density profile in the SERF2 model was about $1.1 \times 10^5 \text{ cm}^{-3}$, while in our standard and enhanced soft X-ray models the values are 4.9×10^4 and $1.2 \times 10^5 \text{ cm}^{-3}$. The Mariner 6 flyby occurred during a period of high solar activity. The lower n_e peak in the Mariner 6 radio occultation profile is significantly less than that in the SERF2 and enhanced X-ray models, about $7 \times 10^4 \text{ cm}^{-3}$. Because of the large variability in the soft X-ray fluxes, as exhibited by the MGS RS electron density profiles, we can only conclude that the soft X-ray fluxes at the time of Mariner 6 were midway between those of our standard and enhanced xray models.

[56] We therefore suggest that our computed ion density lower shoulders are not too small to appear as distinct peaks, but the profiles lack a minimum between the upper and lower peaks. The high altitude peaks also are somewhat too large in the current enhanced X-ray models. We conclude that increasing the Hinteregger fluxes by a uniform factor below 200 Å produces too much ionization near and below the main peaks. We can explore this hypothesis further by considering the altitudes where various wavelengths are absorbed.

[57] The region where solar photons deposit most of their energy is near the altitude where optical depth unity occurs. We can identify the wavelength range that is most important in producing the features in the photoionization profile by reference to a plot of the altitude of unit optical depth as a function of wavelength. We present such plots for the “XUV” wavelength region 0 to 300 Å in Figure 12. In Table 5 we present a summary of various wavelength ranges and the altitude region where optical depth unity is reached in our 60° SZA models. For overhead sun the photons tend to penetrate about 5–7 km further than for 60° SZA. Photons with wavelengths in the main part of the EUV (300–910) are absorbed between 133 and 145 km at low solar activity, and between 138 and 154 km at high solar activity. The F_1 peaks are found near the lower end of this altitude range. The E region shoulders occur near 110 and 115 km for low and high solar activities, respectively. We can see that photons that reach optical depth unity within 5 km of the E region shoulders are characterized by wave-

Table 5. Altitude Range at Which Optical Depth Unity is Reached and Energy Fluxes in That Range as a Function of Wavelength for Our Standard 60° SZA Models

Spectral Range, Å	Low Solar Activity		High Solar Activity	
	Altitude Range, km	Energy Flux, $\text{ergs cm}^{-2} \text{ s}^{-1}$	Altitude Range, km	Energy Flux, $\text{ergs cm}^{-2} \text{ s}^{-1}$
0–14	<100	$1.56(-3)^a$	<107	$3.94(-2)$
14–55	100–105	$2.49(-2)$	107–110	$1.81(-1)$
55–75	105–110	$4.78(-2)$	110–115	$1.50(-1)$
75–100	110–115	$4.62(-2)$	115–120	$1.14(-1)$
100–130	115–120	$1.22(-2)$	120–125	$2.80(-2)$
130–150	120–123	$9.21(-3)$	125–127	$2.39(-2)$
150–200	123–128	$2.04(-1)$	127–133	$5.33(-1)$
200–250	128–131	$8.06(-2)$	133–135	$3.27(-1)$
250–300	131–133	$8.97(-2)$	135–138	$5.74(-1)$
300–910	133–145	$1.00(0)$	138–154	$2.74(0)$

^aRead as 1.56×10^{-3} .

lengths in the range of about 50–100 Å. Photons with wavelengths less than about 130 Å reach optical depth unity at low solar activity below ~120 km and at high solar activity below ~125 km. There are very few solar lines between 130 and 150 Å, but the energy flux in this range is not insignificant. In our models, for minima to occur between the F_1 and E region peaks, the photon fluxes with wavelengths longward of 130–150 Å need to be reduced. Therefore, increasing the solar fluxes with wavelengths up to 200 Å by a uniform factor cannot produce distinct lower peaks in the profiles.

[58] *Solomon et al.* [2001] found better agreement with measured terrestrial electron density profiles by increasing the Hinteregger solar fluxes below 250 Å by a uniform factor of 4. Prior model electron density profiles showed a minimum that did not appear in the incoherent scatter data [e.g., *Buonsanto et al.*, 1992, 1995]. Increasing the photon fluxes with wavelengths up to 250 Å increased the overall ionization rate, and in particular that in the region of the spurious “minimum”. By contrast, we find that the maximum wavelength of the increased fluxes should be less than 200 Å in order to reproduce those MGS profiles that show a distinct E-region peak. Thus while *Solomon et al.* needed to “fill in” a minimum that did not appear in the measured electron density profiles, we need to “carve out” a minimum in the n_e profiles to produce a distinct lower peak. If we were to increase the solar fluxes up to a wavelength of 250 Å, the problems with our model would be exacerbated.

8. Summary and Conclusions

[59] We have compared models of the Martian thermosphere/ionosphere for the standard and enhanced soft X-ray models. Our standard models were computed with the SC#21REFW and F79050 fluxes of Hinteregger, and the enhanced X-ray models were constructed by increasing the standard photon fluxes for wavelengths less than 200 Å by factors of 3 and 6 at low and high solar activities, respectively. We find increases at both the upper peaks and lower shoulders of the ion densities for our enhanced X-ray models. The low altitude “shoulder” in the electron density profile increases by about the square root of the factor by which the solar photon fluxes below 200 Å are assumed to increase. The main F_1 peak is larger by ~10–25%, and the O^+ peak increases by about 16–30%. The lower shoulders in the ion density profiles, other than the major ion O_2^+ , increase by about the same factors as the soft X rays are assumed to increase. In the present models, the shoulders in the n_e density profiles in the E-region do not appear as distinct peaks, as do many of the electron density profiles measured by the MGS Radio Science Experiment (D. P. Hinson and the MGS Radio Science Team, Public access to MGS RS standard electron density profiles, available at <http://nova.stanford.edu/projects/mgs/eds-public.html>, 2003), and the SERF2 models [*Fox et al.*, 1995]. We suggest that the solar fluxes below 200 Å should not be increased by a constant factor, that the upper boundary of the increased fluxes should be ~150 Å or less, or that the fluxes should be increased by larger factors at shorter wavelengths. In general, increasing the solar soft X-ray fluxes up to 200 Å can account for the magnitude of the lower peak seen in the electron density profiles mea-

sured by MGS, but not the minimum that is often observed between the F_1 and E-region peaks.

[60] We also find that the densities of CO_2^+ are significant at the lower shoulder, and are linearly proportional to the increase in the soft X rays. Therefore, if measurements of CO_2^+ were available in the lower thermosphere, the increases in the soft X-ray fluxes could be monitored. In situ measurements in this high neutral density region are only possible with a lander; orbiters generally do not dive into such high density regions, except during aerobraking exercises. Remote sensing of this region by a UV spectrometer on an orbiting spacecraft is not possible. The two features of CO_2^+ in the ultraviolet are the Fox-Duffendack-Barker ($A^2\Pi_u \rightarrow X^2\Pi_g$) bands and the ultraviolet doublet ($B^2\Sigma_u^+ \rightarrow X^2\Pi_g$), very little of either arise from fluorescent scattering of CO_2^+ , and the peaks of these band systems appear near 140 km. It is not known whether the infrared features of ground state CO_2^+ are detectable and sensitive to the CO_2^+ densities of the lower thermospheric region.

[61] The densities of C and NO show little effect of the enhanced X rays, but the peaks in the N density profiles are larger by 23 and 65% at low and high solar activities, respectively. Increasing the solar soft X-ray fluxes up to 200 Å cannot account for the large NO densities observed by Vikings 1 and 2 [*Nier and McElroy*, 1976]. It is possible that the large NO densities measured by the Viking mass spectrometers are an instrumental effect.

[62] We are in the process of constructing models using updated solar spectra. Recent computations using the Solar 2000 v 1.24a spectra of K. Tobiska (private communication, 2003), which are based on the SNOE soft X-ray data, are similar to those we have presented here [*Fox*, 2003b]. Further updates of the Solar 2000 model that are based on the measurements of the TIMED SEE instrument [e.g., *Woods et al.*, 2000] will be used in future models when they become available.

[63] **Acknowledgments.** This work has been supported in part by grant AST0315153 from the National Science Foundation and grants MAG5-13313 and NAG5-12755 from the National Aeronautics and Space Administration.

[64] Arthur Richmond thanks Stephen W. Bougher and another reviewer for their assistance in evaluating this paper.

References

- Acton, L. W., D. C. Weston, and M. E. Bruner (1999), Deriving solar X-ray irradiance from Yohkoh observations, *J. Geophys. Res.*, **104**, 14,827–14,832.
- Anderson, D. E., and C. W. Hord (1971), Mariner 6 and 7 ultraviolet spectrometer experiment: Analysis of hydrogen Lyman alpha, *J. Geophys. Res.*, **76**, 6666–6673.
- Ayres, T. (1997), Evolution of the solar ionizing flux, *J. Geophys. Res.*, **102**, 1641–1651.
- Bailey, S. M., T. N. Woods, C. A. Barth, and S. C. Solomon (1999a), Measurements of the solar soft X-ray irradiance from the Student Nitric Oxide Explorer, *Geophys. Res. Lett.*, **26**, 1255–1258.
- Bailey, S. M., T. N. Woods, L. R. Canfield, R. Korde, C. A. Barth, S. C. Solomon, and J. G. Rottman (1999b), Sounding rocket measurements of the solar soft X-ray irradiance, *Sol. Phys.*, **186**, 243–257.
- Bailey, S. M., T. N. Woods, C. A. Barth, S. C. Solomon, L. R. Canfield, and R. Korde (2000), Measurements of the solar soft X-ray irradiance by the Student Nitric Oxide Explorer: First analysis and underflight calibrations, *J. Geophys. Res.*, **105**, 27,179–27,193.
- Baluja, K. L., and C. J. Zeippen (1988), M1 and E1 transition probabilities for state within the $2p^4$ configurations of the O I isoelectronic sequence, *J. Phys. B*, **21**, 1455–1471.
- Banks, P. M., and G. Kockarts (1977), *Aeronomy*, vol. A, pp. 144–146, Academic, San Diego, Calif.

- Barth, C. A. (1996), Reference models for thermospheric nitric oxide, 1994, *Adv. Space Res.*, 18(9/10), 179–208.
- Barth, C. A., W. K. Tobiska, D. E. Siskind, and D. D. Cleary (1988), Solar-terrestrial coupling: Low latitude thermospheric nitric oxide, *Geophys. Res. Lett.*, 15, 92–94.
- Barth, C. A., S. C. Bailey, and S. C. Solomon (1999), Solar-terrestrial coupling: Solar soft X rays and thermospheric nitric oxide, *Geophys. Res. Lett.*, 26, 1251–1254.
- Barth, C. A., K. D. Manikoff, S. M. Bailey, and S. C. Solomon (2003), Global observations of nitric oxide in the thermosphere, *J. Geophys. Res.*, 108(A1), 1027, doi:10.1029/2002JA009458.
- Bauer, S. J. (1973), *Physics of Planetary Ionospheres*, 223 pp., Springer-Verlag, New York.
- Bougher, S. W., R. G. Roble, E. C. Ridley, and R. E. Dickinson (1990), The Mars thermosphere: 2. General circulation with coupled dynamics and composition, *J. Geophys. Res.*, 95, 14,811–14,827.
- Bougher, S. W., S. Engel, R. G. Roble, and B. Foster (1999), Comparative terrestrial planet thermospheres: 2. Solar cycle variation of global structure and winds at solstices, *J. Geophys. Res.*, 104, 16,591–16,611.
- Bougher, S. W., S. Engel, R. G. Roble, and B. Foster (2000), Comparative terrestrial planet thermospheres: 3. Solar cycle variation of global structure and winds at solstices, *J. Geophys. Res.*, 105, 17,669–17,692.
- Bougher, S. W., S. Engel, D. P. Hinson, and J. M. Forbes (2001), Mars Global Surveyor Radio Science electron density profiles: Neutral atmosphere implications, *Geophys. Res. Lett.*, 28, 3091–3094.
- Brown, R., and C. A. Winkler (1970), The chemical behaviour of active nitrogen, *Angew. Chem.*, 9, 181–254.
- Buonsanto, M. J., S. C. Solomon, and W. K. Tobiska (1992), Comparison of measured and modeled solar EUV flux and its effect on the $E - F$ region of the ionosphere, *J. Geophys. Res.*, 97, 10,513–10,524.
- Buonsanto, M. J., P. G. Richards, W. K. Tobiska, S. C. Solomon, Y.-K. Tung, and J. Fennelly (1995), Ionospheric electron densities calculated using different EUV flux models, and cross sections: Comparison with radar data, *J. Geophys. Res.*, 100, 14,569–14,580.
- Butler, K., and C. J. Zeippen (1984), NI forbidden lines revisited, *Astron. Astrophys.*, 141, 274–278.
- Chapman, S. (1931), The absorption and dissociative or ionizing effects of monochromatic radiation in an atmosphere of a rotating earth, *Proc. Phys. Soc. London*, 43, 26–45.
- Chen, R. H., T. E. Cravens, and A. F. Nagy (1978), The Martian ionosphere in light of the Viking observations, *J. Geophys. Res.*, 83, 3871–3876.
- Cleary, D. D. (1986), Daytime high-latitude rocket observations of the γ , δ , and ϵ bands, *J. Geophys. Res.*, 91, 11,337–11,344.
- Conway, R. R. (1984), Comments of the interpretation of 3371 Å filter-photometer observations and its implications for the AE-E photoelectron fluxes, *Planet. Space Sci.*, 31, 1223–1228.
- Dalgarno, A., and J. L. Fox (1994), Ion chemistry in atmospheric and astrophysical plasmas, in *Unimolecular and Bimolecular Reaction Dynamics*, edited by C. Y. Ng, T. Baer, and I. Powis, pp. 1–85, John Wiley, Hoboken, N. J.
- Daltabuit, E., and D. P. Cox (1972), K -shell photoionization cross sections, *Astrophys. J.*, 177, 855–859.
- DeMore, W. B., S. P. Sander, D. M. Golden, R. F. Hampson, M. J. Kurylo, C. J. Howard, A. R. Ravishankara, C. E. Kolb, and M. J. Molina (1992), Chemical kinetics and photochemical data for use in stratospheric modeling, evaluation number 10, *JPL Publ.*, 92-20, 240 pp.
- DeMore, W. B., S. P. Sander, D. M. Golden, R. F. Hampson, M. J. Kurylo, C. J. Howard, A. R. Ravishankara, C. E. Kolb, and M. J. Molina (1994), Chemical kinetics and photochemical data for use in stratospheric modeling, evaluation number 11, *JPL Publ.*, 94-26, 284 pp.
- Duff, J. W., and R. D. Sharma (1997), Quasiclassical trajectory study of the $N(^4S) + NO(X^1\Sigma) \rightarrow N_2(X^1\Sigma_g^+) + O(^3P)$ reaction cross section on the excited $^3A'$ NNO surface, *Chem. Phys. Lett.*, 265, 404–409.
- Ferguson, E. E. (1973), Rate constants of the thermal energy binary ion-molecule reactions of aeronomic interest, *At. Data Nucl. Data Tables*, 12, 159–178.
- Fjeldbo, G., A. Kliore, and B. Seidel (1970), The Mariner 1969 occultation measurements of the upper atmosphere of Mars, *Radio Sci.*, 5, 381.
- Fox, J. L. (1992), Airglow and aurora in the atmospheres of Venus and Mars, in *Venus and Mars: Atmospheres, Ionospheres, and Solar Wind Interaction*, *Geophys. Monogr. Ser.*, vol. 66, edited by J. G. Luhmann, M. Tatrallyay, and R. Pepin, pp. 191–222, AGU, Washington, D. C.
- Fox, J. L. (1993), The production and escape of nitrogen atoms on Mars, *J. Geophys. Res.*, 98, 3297–3310.
- Fox, J. L. (1994), Rate coefficient for the reaction $N + NO$, *J. Geophys. Res.*, 99, 6273–6276. (Corrigendum, *J. Geophys. Res.*, 101, 1987, 1996.)
- Fox, J. L. (1997), Upper limits to the outflow of ions at Mars: Implications for atmospheric evolution, *Geophys. Res. Lett.*, 24, 2901–2904.
- Fox, J. L. (2001), The effect of enhanced hydrogen on the nonthermal escape of atoms, *Eos Trans. AGU*, 82(20), Spring Meet. Suppl., S249.
- Fox, J. L. (2003a), The effect of H_2 on the Martian ionosphere: Implications for atmospheric evolution, *J. Geophys. Res.*, 108(A6), 1223, doi:10.1029/2001JA000203.
- Fox, J. L. (2003b), The effects of enhanced fluxes of soft X rays on the ionospheres and thermospheres of Venus and Mars, *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract A12A-70.
- Fox, J. L., and F. B. Bakalian (2001), Photochemical escape of atomic carbon from Mars, *J. Geophys. Res.*, 106, 28,785–28,791.
- Fox, J. L., and A. Dalgarno (1979), Ionization, luminosity, and heating of the upper atmosphere of Mars, *J. Geophys. Res.*, 84, 7315–7333.
- Fox, J. L., and A. Hać (1997), The spectrum of hot O at the exobases of the terrestrial planets, *J. Geophys. Res.*, 102, 24,005–24,011.
- Fox, J. L., and K. Y. Sung (2001), Solar activity variations in the Venus ionosphere/thermosphere, *J. Geophys. Res.*, 106, 21,305–21,335.
- Fox, J. L., P. Zhou, and S. W. Bougher (1995), The thermosphere/ionosphere of Mars at high and low solar activities, *Adv. Space Res.*, 17(11), 203–218.
- Gamallo, P., M. González, and R. Sayós (2003), Ab initio study of the two lowest triplet potential energy surfaces involved in the $N(^4S) + NO(X^2\Pi)$ reaction, *J. Chem. Phys.*, 118, 10,602–10,610.
- Gauyacq, D., C. Larcher, and J. Rostas (1979), The emission spectrum of the CO_2^+ ion: Rovibronic analysis of the $A^2\Pi_u \rightarrow X^2\Pi_g$ band system, *Can. J. Phys.*, 57, 1634–1649.
- Gérard, J.-C., and C. A. Barth (1977), High-latitude nitric oxide in the lower thermosphere, *J. Geophys. Res.*, 82, 674.
- Gérard, J.-C., R. G. Roble, D. W. Rusch, and A. I. Stewart (1984), The global distribution of thermospheric odd nitrogen for solstice conditions during solar cycle maximum, *J. Geophys. Res.*, 89, 1725–1738.
- Hanson, W. B., S. Sanatani, and D. R. Zuccaro (1977), The Martian ionosphere as observed by the Viking retarding potential analyzers, *J. Geophys. Res.*, 82, 4351–4367.
- Heroux, L., and J. E. Higgins (1977), Summary of full disk solar fluxes between 250 and 1940 Å, *J. Geophys. Res.*, 82, 3307.
- Heroux, L., and H. E. Hinteregger (1978), Aeronomic reference spectrum for solar UV below Å, *J. Geophys. Res.*, 83, 5305–5308.
- Herron, J. T., and R. E. Huie (1968), On the reaction of atomic nitrogen with carbon dioxide, *J. Phys. Chem.*, 72, 2235.
- Hinteregger, H. E., K. Fukui, and B. R. Gibson (1981), Observational, reference, and model data on solar EUV, from measurements on AE-E, *Geophys. Res. Lett.*, 8, 1147–1150.
- Jin, H., T. Mukai, T. Tanaka, and K. Maezawa (2001), Oxygen ions escaping from the dayside Martian upper atmosphere, *Adv. Space Res.*, 27(11), 1825–1830.
- Kallio, E., H. Koskinen, S. Barabash, C. M. C. Nairn, and K. Schwingenshuh (1995), Oxygen outflow in the Martian magnetotail, *Geophys. Res. Lett.*, 22, 2449–2452.
- Kella, D., L. Vejby-Christensen, P. J. Johnson, H. B. Pedersen, and L. H. Andersen (1997), The source of green light emission determined from a heavy-ion storage ring experiment, *Science*, 276, 1530–1533.
- Kirby, K., E. R. Constantinescu, S. Babeu, M. Oppenheimer, and G. A. Victor (1979), Photoionization and photoabsorption cross sections of He, O, N_2 , and O_2 for aeronomic calculations, *At. Data Nucl. Data Tables*, 23, 63–78.
- Kopp, J. P., D. W. Rusch, R. G. Roble, G. A. Victor, and P. B. Hayes (1977), Photoemission in the second positive system of molecular nitrogen in the Earth's airglow, *J. Geophys. Res.*, 82, 555.
- Krasnopolsky, V. A. (1993), Photochemistry of the Martian atmosphere (mean conditions), *Icarus*, 101, 313–332.
- Krasnopolsky, V. A. (2002), Mars' upper atmosphere and ionosphere at low, medium, and high solar activities: Implications for evolution of water, *J. Geophys. Res.*, 107(E12), 5128, doi:10.1029/2001JE001809.
- Krasnopolsky, V. A., and P. D. Feldman (2001), Detection of molecular hydrogen in the atmosphere of Mars, *Science*, 294, 1914–1917.
- Krasnopolsky, V. A., and G. R. Gladstone (1996), Helium on Mars: EUVE and PHOBOS data and implications for Mars' evolution, *J. Geophys. Res.*, 101, 15,765–15,772.
- Krasnopolsky, V. A., M. J. Mumma, and G. R. Gladstone (1998), Detection of atomic deuterium in the upper atmosphere of Mars, *Science*, 280, 1576–1580.
- Lee, J. H., J. V. Michael, W. A. Payne, and L. Stief (1978), Absolute rate of the reaction of $N(^4S)$ with NO from 196–400 K with DF-RF and FP-RF techniques, *J. Chem. Phys.*, 69, 3069–3076.
- Lee, J. S., J. P. Doering, T. A. Potemra, and L. H. Brace (1980), Measurements of the ambient photoelectron spectrum from Atmosphere Explorer: I. AE-E measurements below 300 km during solar minimum conditions, *Planet. Space Sci.*, 28, 947–971.
- Lichtenegger, H., and E. Dubinin (1998), Magnetotail calculations of the planetary ion distribution in the Martian tail, *Earth Planets Space*, 50, 445–452.

- Lindsay, B. G., M. A. Mangan, H. C. Straub, and R. F. Stebbings (2000), Absolute partial cross sections for electron-impact ionization of NO and NO₂ from threshold to 1000 eV, *J. Chem. Phys.*, **112**, 9404–9410.
- Liu, Y., A. F. Nagy, T. I. Gombosi, D. L. DeZeeuw, and K. G. Powell (2001), The solar wind interaction with Mars: Results of three-dimensional three-species MHD Studies, *Adv. Space. Res.*, **27**(11), 1837–1846.
- Lundin, R., A. Zhakarov, R. Pellinen, H. Borg, B. Hultquist, N. Pissarenko, E. Dubinen, S. Barabash, I. Liede, and H. Koskinen (1989), First measurements of the ionospheric plasma escape from Mars, *Nature*, **341**, 609–612.
- Lundin, R., A. Zhakarov, R. Pellinen, S. W. Barabash, H. Borg, E. Dubinen, B. Hultquist, H. Koskinen, I. Liede, and N. Pissarenko (1990), ASPERA/PHOBOS measurements of the ion outflow from the Martian ionosphere, *Geophys. Res. Lett.*, **17**, 873–876.
- Ma, Y., A. F. Nagy, K. C. Hansen, D. L. DeZeeuw, and K. G. Powell (2002), Three-dimensional multispecies MHD studies of the solar wind interaction with Mars in the presence of crustal fields, *J. Geophys. Res.*, **107**(A10), 1282, doi:10.1029/2002JA009293.
- Ma, Y., A. F. Nagy, I. V. Sokolov, and K. C. Hansen (2004), Three-dimensional, multispecies, high spatial resolution MHD studies of the solar wind interaction with Mars, *J. Geophys. Res.*, **109**, A07211, doi:10.1029/2003JA010367.
- McElroy, M. B., T. Y. Kong, Y. L. Yung, and A. O. Nier (1976), Composition and structure of the Martian atmosphere: Analysis and results from Viking, *Science*, **194**, 1295–1298.
- Nier, A. O., and M. B. McElroy (1976), Structure of the neutral upper atmosphere of Mars: Results from Viking 1 and Viking 2, *Science*, **194**, 1298–1300.
- Nier, A. O., and M. B. McElroy (1977), Composition of structure of Mars' upper atmosphere: Results from the neutral mass spectrometers on Viking 1 and 2, *J. Geophys. Res.*, **82**, 4341–4349.
- Nier, A. O., W. B. Hanson, A. Seiff, M. B. McElroy, N. W. Spencer, R. J. Duckett, T. C. D. Knight, and W. S. Cook (1976), Composition and structure of the Martian atmosphere: Preliminary results from Viking I, *Science*, **193**, 786–788.
- Ogawa, H. S., and D. L. Judge (1986), Absolute solar flux measurement shortward of 575 Å, *J. Geophys. Res.*, **91**, 7089–7092.
- Petrinec, S. M., W. L. Imhof, C. A. Barth, K. D. Mankoff, D. N. Baker, and J. G. Luhmann (2003), Comparison of thermospheric high-latitude nitric oxide observations from PIXIE, *J. Geophys. Res.*, **108**(A3), 1123, doi:10.1029/2002JA009451.
- Peverall, R., et al. (2001), Dissociative recombination and excitation of O₂⁺: Cross sections, product yields, and implications for studies of atmospheric airglow, *J. Chem. Phys.*, **114**, 6679–6689.
- Richards, P. G., and D. G. Torr (1984), An investigation of the consistency of the ionospheric measurements of the photoelectron flux and solar EUV flux, *J. Geophys. Res.*, **89**, 5625–5635.
- Richards, P. G., J. A. Fennelly, and D. G. Torr (1994), EUVAC: A solar EUV flux model for aeronomic calculations, *J. Geophys. Res.*, **99**, 8981–8992.
- Sander, S. P., et al. (2003), Chemical kinetics and photochemical data for use in atmospheric studies, evaluation number 14, *JPL Publ.*, 02-25.
- Shinagawa, H., and T. E. Cravens (1989), A one-dimensional multispecies magnetohydrodynamic model of the dayside ionosphere of Mars, *J. Geophys. Res.*, **94**, 6506–6516.
- Shizgal, B., and R. Blackmore (1986), A collisional kinetic theory of a plane parallel evaporating planetary atmosphere, *Planet. Space Sci.*, **34**, 279–291.
- Solomon, S. C., S. M. Bailey, and T. N. Woods (2001), Effect of solar soft X rays on the lower ionosphere, *Geophys. Res. Lett.*, **28**, 2149–2152.
- Stewart, A. I. (1972), Mariner 6 and 7 ultraviolet spectrometer experiment: Implications of CO₂⁺, CO, and O airglow, *J. Geophys. Res.*, **77**, 54–68.
- Stewart, A. I. F., R. R. Meier, L. J. Paxton, S. W. Bougher, and C. G. Fesen (1992), Atomic oxygen in the Martian thermosphere, *J. Geophys. Res.*, **97**, 91–102.
- Straub, H. C., P. Renault, B. G. Lindsay, K. A. Smith, and R. F. Stebbings (1996), Absolute partial cross sections for electron-impact ionization of H₂, N₂, and O₂ from threshold to 1000 eV, *Phys. Rev. A*, **54**, 2146–2153.
- Strickland, D. J., J. Bishop, J. S. Evans, T. Majeed, P. M. Shen, R. J. Cox, R. Link, and R. E. Huffman (1999), Atmospheric Ultraviolet Radiance Integrated Code (AURIC): Theory, software, inputs, and selected results, *J. Quant. Spectrosc. Radiat. Transfer*, **62**, 689–742.
- Swaminathan, P. K., et al. (1998), Nitric oxide abundance in the mesosphere lower thermosphere region: Roles of solar soft X rays, suprathermal N(⁴S) atoms, and vertical transport, *J. Geophys. Res.*, **103**(A6), 11,579–11,594.
- Tobiska, W. K. (1991), Revised solar extreme ultraviolet flux model, *J. Atmos. Terr. Phys.*, **53**, 1005–1018.
- Torr, M. R., D. G. Torr, R. A. Ong, and H. E. Hinteregger (1979), Ionization frequencies for major thermospheric constituents as a function of solar cycle 21, *Geophys. Res. Lett.*, **6**, 771–774.
- Tyler, G. L., et al. (2001), Radio science observations with Mars Global Surveyor: Orbit insertion through one Mars year in mapping orbit, *J. Geophys. Res.*, **106**, 23,327–23,348.
- Verigin, M. I., et al. (1991), Ions of planetary origin in the Martian magnetosphere (Phobos/TAUS experiment), *Planet. Space Sci.*, **39**, 131–137.
- Verner, D. A., and D. G. Yakovlev (1995), Analytic fits for partial photoionization cross sections, *Astron. Astrophys. Suppl. Ser.*, **109**, 125–133.
- Weisheit, J. C. (1974), X-ray ionization cross sections and ionization equilibrium equations modified in Auger transitions, *Astrophys. J.*, **190**, 735–740.
- Wennberg, P. O., J. G. Anderson, and D. K. Weisenstein (1994), Kinetics of reactions of ground state nitrogen atoms (⁴S_{3/2}), *J. Geophys. Res.*, **99**, 18,839–18,846.
- Woods, T. N., et al. (2000), TIMED Solar EUV Experiment, *Phys. Chem. Earth, Part C, Sol. Terr. Planet. Sci.*, **25**, 393–396.
- Zeippen, C. J. (1982), Transition probabilities for forbidden lines in the 2p³ configuration, *Mon. Not. R. Astron. Soc.*, **198**, 111–125.

J. L. Fox, Department of Physics, Wright State University, Dayton, OH 45435, USA. (jane.fox@wright.edu)