Photoelectrons and solar ionizing radiation at Mars: Predictions versus MAVEN observations

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Abstract Understanding the evolution of the Martian atmosphere requires knowledge of processes transforming solar irradiance into thermal energy well enough to model them accurately. Here we compare Martian photoelectron energy spectra measured at periapsis by Mars Atmosphere and Volatile Evolution Mission (MAVEN) with calculations made using three photoelectron production codes and three solar irradiance models as well as modeled and measured CO₂ densities. We restricted our comparisons to regions where the contribution from solar wind electrons and ions were negligible. The two intervals examined on 19 October 2014 have different observed incident solar irradiance spectra. In spite of the differences in photoionization cross sections and irradiance spectra used, we find agreement between models to be within the combined uncertainties associated with the observations from the MAVEN neutral density, electron flux, and solar irradiance instruments.

1. Introduction

Solar ionizing radiation at wavelengths below about 90 nm incident on the Martian ionosphere and thermosphere is a primary energy source for these regions. Solar irradiance below 90 nm often varies by factors of up to 100 over the solar disk [e.g., Chamberlin et al., 2007, 2008]. Earth and Mars are generally exposed to different ranges of solar longitudes and thus different irradiance below 90 nm. Until the launch of Mars Atmosphere and Volatile Evolution Mission (MAVEN) there were no systematic observations of the solar irradiance incident on Mars. Consequently, uncertainties in the solar irradiance incident on Mars were significantly larger than those on Earth. By reducing uncertainties in our understanding of the short-wavelength solar irradiance impacting Mars, we can improve our ability to model the Martian atmosphere.

The process of converting solar irradiance to thermal energies begins with photoionization in the Martian thermosphere. A technique for estimating our understanding of this process is to compare observed Martian suprathermal electrons with those calculated by well-tested codes using various estimates of solar irradiance and neutral density. Instruments on the MAVEN now provide broadband solar irradiance data, neutral density data, and suprathermal electron energy spectra that can be used to assess our understanding of solar energy input and our ability to model the production of Martian photoelectrons [Jakosky et al., 2015].

There have been numerous investigations of suprathermal Martian electrons. Initially, they were used to identify field lines coming from the ionosphere as described in the review of Frahm et al. [2006]. Recently, Peterson et al. [2013] attempted to deduce variations in short-wavelength solar radiation at Mars from variations in suprathermal electron energy spectra observed on the Mars Global Surveyor (MGS) satellite. The MGS survey data used in the 2013 study were acquired well above the primary photoelectron production region, so Peterson and his colleagues developed procedures to identify photoelectrons streaming up magnetic field lines from the primary production altitude between 150 and 200 km. The attempt to use variations in MGS electron spectra to monitor variations in short-wavelength solar irradiance was not successful because of the very small number of intervals of MGS data near 400 km without a significant noise signal from solar wind.
electrons. Xu et al. [2015a] compared photoelectron energy spectra calculated using their multistream SuperThermal Electron Transport (STET) model and two different models of solar irradiance. They found that the calculated photoelectron spectra agreed mostly to within a factor of 2. Sakai et al. [2015] used a different two-stream code developed at Kansas University (KS) and solar irradiances from the Heliospheric Environment Solar Spectral Radiation (HESSR) model [Fontenla et al., 2009, 2011] to model suprathermal electron observations. The Sakai et al. [2015] analysis suggested that differences between the calculations and observations could be explained by reducing the HESSR irradiance in the 30 nm range.

Here we focus on the production of photoelectrons below 200 km, where transport is not a dominant process.

2. Data and Models

2.1. Suprathermal Electron Data

Figure 1 presents two suprathermal electron energy spectra (symbols) and the signal-to-noise ratio (S/N, solid lines) of observations obtained on 19 October 2014 before (01:29:36 UT, black) and after (06:04:50 UT, orange) an X class flare that was detected at 05:08 on 19 October 2014. The omnidirectional data from the MAVEN Solar Wind Electron Analyzer (SWEA) [Mitchell et al., 2016] were acquired over 16 s and have been corrected for the spacecraft potential measured by the Langmuir Probe and Waves instrument on MAVEN (LPW) [Andersson et al., 2015]. The spacecraft potential and other observational parameters for the two times are given in Table 1. Here the signal-to-noise ratio is calculated from the ratio of the observed signal to the square root of its variance. The dotted horizontal line in Figure 1 indicates a S/N of 3, the lowest value where uncertainties associated with the detector count rate are negligible. As expected, the fluxes of electrons with energies above ~ 56 eV are seen after the flare. The S/N ratio is greater than 3 below 585 eV preflare and below 800 eV postflare.

We compare and contrast observed suprathermal electron and calculated photoelectron spectra before and after an X class flare that was seen at Mars on 19 October 2014 at 05:08 UT. We use the three photoelectron production codes noted above, modeled and measured neutral densities, and several approaches to model the solar irradiance spectrum at 1 nm resolution before and after the X class flare.

![Figure 1. Electron spectra (symbols) and the associated signal-to-noise value (lines) observed on MAVEN before (black) and after (orange) an X class flare that was detected at 05:08 on 19 October 2014. The times and other observational details are given in Table 1. Signal-to-noise ratio (S/N) is defined as the ratio of the observed flux to the square root of the associated measurement variance. The dotted horizontal line indicates a S/N of 3. Vertical dotted lines are shown at 10, 20, 56, 200, 585, and 800 eV, energies that are noted in the text. Increased fluxes above ~ 56 eV are seen after the flare. The S/N ratio is greater than 3 below 585 eV preflare and below 800 eV postflare.](image-url)
2.2. Solar Data and Models

We use two models of the solar irradiance incident on Mars: (1) the MAVEN Level 3 data product (L3D), which is a modification of the Flare Irradiance Spectral Model (FISM) [Chamberlin et al., 2007, 2008] expanded by MAVEN observations [Eparvier et al., 2015], and (2) the Heliospheric Environment Solar Spectral Radiation (HESR) [Fontenla et al., 2009, 2011] irradiance model. As noted by Xu et al. [2015a] both Martian irradiance spectra models use Earth-based assets but different approaches to account for the temporal and spectral variability of extreme ultraviolet (EUV) and soft X-ray (XUV) irradiance over the solar surface. The HESSR approach is to compute the solar irradiance from the portion of full disk solar EUV images obtained from near-Earth orbit that are visible to an observer on Mars. The other model is derived from MAVEN data and is formally designated the MAVEN R1V2 EUVM Level 3 data product. This data product is available on daily and minute cadences (Level 3 daily: L3D and Level 3 (black) and the L3FR model (red). Vertical dotted lines are shown at 2, 6, 17, 31, 50, and 65 nm. Integral irradiance over 0–6, 6–17, 17–31, 31–50, and 0–50 nm are shown as solid lines colored to correspond with the spectra. The spectra in Figure 2a are used for preflare model runs; the spectra in Figure 2b are used in the postflare model runs.

Photoelectrons with energies greater than 10 eV are produced by photons with wavelengths shorter than 50 nm. Photoelectrons with wavelengths shorter than 50 nm. Figure 2 presents models of the solar irradiance spectra from 0 to 100 nm for the preflare and postflare times indicated in Table 1. The black lines in Figure 2a show the L3D spectrum for 19 October 2014. Two versions of the postflare irradiance spectrum are shown in Figure 2b. The black lines are the 1 min cadence L3F model. The red lines show the L3D data product scaled by spectral measurements of preflare/postflare intensity seen at Earth by the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED)/Solar Extreme Ultraviolet Experiment (SEE) instrument [Woods et al., 1998] and denoted as L3FR below. Vertical dotted lines are shown in Figure 2 at 6, 17, 31, and 50 nm. Integral irradiance over 0–6, 6–17, 17–31, 31–50, and 0–50 nm bands are shown as solid lines colored to correspond with the spectra.
The total solar irradiance incident on Mars is about one half that incident on Earth or ~500 W/m². Of that less than $10^{-2}$ W/m² occurs at wavelengths less than 50 nm. The postflare intensification in electron flux at energies above ~56 eV in Figure 1 is produced by solar irradiance below 17 nm shown in Figure 2b. The significant differences between the two irradiance spectra shown in Figure 2a between 56 and 100 nm produce different photoelectron fluxes with energies less than ~6 eV shown in Figure 1. We note also that in the preflare spectra below 50 nm the distribution of intensity differs primarily in the 6–31 nm range where the HESSR irradiance spectrum has about 30% more power than the L3D spectrum. The postflare spectra shown in Figure 2b differ mostly in the 6–17 nm range.

2.3. Neutral Density and Models

The neutral density in the region below 200 km examined here is dominated by CO₂. In situ observations of CO₂ density are available from the MAVEN Neutral Gas and Ion Mass Spectrometer [Mahaffy et al., 2015] and model values that have been validated against many previous Mars missions from the Mars Global Ionosphere-Thermosphere Model (M-GITM) [Bougher, 2012; Bougher et al., 2015a]. Bougher et al. (2015b) reported agreement within observational uncertainty of ~7% between Neutral Gas and Ion Mass Spectrometer (NGIMS) and M-GITM between 180 and 200 km during a MAVEN deep-dip campaign in April 2015.

Our analysis compares measured and modeled photoelectron energy spectra. In the analysis below we begin by using CO₂ densities from the M-GITM simulation with an Earth $F_{10.7} = 130$ sfu (solar flux unit; 1 sfu $= 10^{-22}$ W m⁻² Hz⁻¹). We show section 3 below that the M-GITM model and NGIMS Version 6 CO₂ densities differ by less than 12%.

2.4. Photoelectron Production Codes

To explore the uncertainties in our understanding of solar irradiance energy input to the Martian system using the data and solar irradiance spectra presented above, we use three photoelectron production codes: the University of Michigan STET (Super Thermal Electron Transport) code [Liemohn et al., 2003; Xu and...
Liemohn, 2015; Xu et al., 2015a], the University of Kansas two-stream code (denoted as KS below) [Cravens et al., 2004; Sakai et al., 2015], and the Atmospheric Ultraviolet Radiance Integrated Code (AURIC) [Strickland et al., 1999]. These codes incorporate similar sets of photoelectron production cross sections and are commonly used in the study of planetary atmospheres.

In addition to knowledge of the solar irradiance spectrum, these codes also require data on the neutral density and composition. In this initial assessment the AURIC and STET models use neutral density and composition values at latitude 52.5° and longitude 47.5° obtained from the Mars Global Ionosphere-Thermosphere Model (M-GITM) [Bougher, 2012; Bougher et al., 2015a], from a simulation run with an Earth F$_{10.7} = 130$ sfu. The KS model used slightly different neutral densities. The KS CO$_2$ densities are identical with the M-GITM model, but the O and CO densities are 30% lower in the KS model. Given that CO$_2$ is the dominant species below 200 km, these differences do not affect the calculated electron fluxes.

Below we first compare the data and models using the M-GITM model CO$_2$ densities. We subsequently discuss the implications of the small differences between the M-GITM model and NGIMS Version 6 CO$_2$ densities.

### 3. Data-Model Comparison

Figure 3 repeats the observed preflare and postflare electron spectra and signal-to-noise ratio as solid and dash-dotted black lines. The model results have been convolved with an instrument response function [Mitchell et al., 2016] to facilitate comparison with observations. Symbols display calculated photoelectron spectra as follows: plus symbols, STET; asteriskd, AURIC; and open diamonds, KS. Model results using the L3D (Figure 3a) and L3F (Figure 3b) models are encoded using black symbols. Green symbols show results calculated using HESSR irradiance values at Mars, and red symbols show values calculated using the L3FR model. Vertical dotted lines are drawn at 10, 20, 56, and 200 eV marking the boundaries of energy bands discussed below. The most striking features in Figure 3 are the agreement between models and observations between about 10 and 56 eV and the disagreement between specific models and observations above and below these energies.

![Figure 4. Relative difference between observed and modeled electron flux values as a function of energy shown in Figure 3.](image)
The large dynamic range of the electron fluxes shown in Figure 3 impedes detailed visual inspection of the agreement between observed and modeled electron spectra. Figure 4 presents an alternative way to display the differences between models and observations. Figure 4 shows the same model calculations presented in Figure 3 that are encoded with the same symbols and colors for comparison with observations. The relative difference reported in Figure 4 is the difference between the modeled and observed fluxes divided by the observed fluxes plotted as a function of energy. A value of 0 (middle dotted horizontal line) indicates model data agreement. A value of ±0.5 (top and bottom horizontal dotted lines) indicates that the data and models disagree by 50%.

The energies indicated by vertical dotted lines in Figure 4 at 10, 20, 56, 200, 575, and 800 eV mark boundaries of different qualities of data-model agreement. Figure 5 presents integrals of the differences over the energy range of each of the four energy bands identified in Figure 4 divided by the width of the band in eV. This could best be called effective difference per eV. The format emphasizes consistent differences over the individual energy bands. Note that the preflare high-energy band in Figure 5a is from 200 to 575 eV and the postflare band in Figure 5b is from 200 to 800 eV. The upper limits...
use of the AURIC code. All cross sections show a broad peak from 30 to ~70 nm. Below ~17 nm the cross sections used by the AURIC and KS codes are significantly lower than that used by the STET code, except for the Auger photoionization features at 2.2 and 4.4 nm, corresponding to electrons of 500 and 250 eV, respectively [e.g., Moddeman et al., 1971], which are not included in the STET code. The STET code, however, includes the double ionization cross sections for CO2 which are not shown in Figure 7.

Photoionization by solar irradiance shorter than 42 nm produces electrons with enough energy to ionize CO2 and create secondary electrons. These secondary electrons are part of the observed suprathermal electron energy spectrum. The photoelectron codes used here capture this component of the photoelectron spectra. Figure 8 presents the electron impact ionization cross sections for CO2 used by the three codes noted above. The cross sections peak at ~100 eV where the one used by the KS code is about 20% lower. The falloff in cross section value below 20 eV is qualitatively different for the three codes. The AURIC cross section extends below the CO2 ionization potential (13.7 eV) reflecting the fact that the cross sections used in the AURIC code include electron impact ionization of excited states of CO2.

Differences of the spectral resolution of the photoionization cross sections shown in Figure 7 will have the largest impact on the calculated photoelectron flux where there is structure in the cross sections, i.e., below 6 nm and above 65 nm corresponding to electrons with energies greater than 200 eV and less than 5 eV, respectively. Differences in the magnitude of the electron impact cross sections will impact the calculated photoelectron spectra for wavelengths longer than ~35 nm which produce secondary electrons with energies less than 20 eV. We cannot make a data-model comparison for ionization produced by wavelengths greater than 65 nm because observations extend only to 5 eV in the plasma frame of reference.

### 4.3. Detailed Data/M-GITM-Based Model Comparisons

The relative difference between modeled and observed electron spectra is defined as (model flux – observed flux)/observed flux. Figure 4 presents the relative differences as a function of energy. Figure 5 presents them for four selected energy bands. Values of ± 0.5 (top and bottom horizontal dotted lines) indicate that the data and models disagree by 50%. Positive values indicate that the modeled fluxes are larger than the observations. In general, the disagreement between models and data between 5 and 800 eV is less than 50%, i.e., within uncertainties associated with the data. The agreement between data and models is, however, not uniform in energy. In the sections below we address differences in three broad energy ranges.

#### 4.3.1. Energies Above 200 eV

The photoelectron spectra calculated with all three codes agree remarkably well with observations above 200 eV. Figure 5 shows that the model fluxes, on average, agree best with those calculated using the STET code above 200 eV. The fluxes from the AURIC code are higher, and those from the KS code are lower. Two codes (AURIC and KS) make some provision for calculating the effects of the narrow Auger electron lines near 250 and 500 eV. We consider preflare and postflare data-model comparisons separately.

Postflare, the differences in the two irradiance spectra below 6 nm are mostly in the 2 nm bin which produces electrons with energies that are detected in the energy channel centered on 568 eV and include a contribution from Auger electrons near 500 eV. In the region around the 250 eV Auger line the AURIC and STET codes agree quite well with the data and the KS code predicts systematically lower fluxes. Agreement between the

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**Figure 8.** Total CO2 electron impact ionization cross sections as a function of wavelength used in the photoelectron production codes. The cross sections are color coded as follows STET [from Fox and Sung, 2001]: black, KS [from Gan and Cravens, 1990, and references therein]: orange, and AURIC: red. The vertical dashed line at 13.7 eV denotes the ionization threshold for CO2. Vertical dotted lines are also shown at 20, 56, 200, 585, and 800 eV.
codes and data in the 505 and 568 eV energy channels is different. The AURIC code predicts significantly higher fluxes than those observed, while the KS and STET codes give about the same agreement with observations that were seen near the 250 eV Auger line. The KS code predicts lower electron fluxes than those observed. This reflects the lower value of the photoionization cross section compared to the STET code and lower energy resolution compared to the AURIC code.

Figure 2 shows that the preflare L3D and HESSR integrated irradiance power below 6 nm is about the same, but the distributions in wavelength are different. The L3D irradiance values peak in the 1 nm bin, whereas the HESSR values are approximately uniform in intensity from 2 to 6 nm. Both postflare irradiance spectra below 6 nm in Figure 2b have the same shape as the L3D irradiance spectra shown in Figure 2a. Preflare data-model agreement using L3D irradiance spectra (black symbols in Figure 4a) is similar to postflare agreement shown in Figure 4b. Here again the AURIC code predicts significantly higher fluxes than observed. Preflare data-model comparisons made using the HESSR irradiance spectra are shown as green symbols in Figure 4a. We see that the AURIC code again predicts significantly more electron flux over most of the energy steps sampled above 200 eV. Between 200 and 400 eV this reflects the significantly more intense HESSR irradiance spectra between 2 and 6 nm. The preflare agreement with the KS code is similar to the postflare case. We note that Moddeman et al. [1971] do not report C, N, or O Auger electron emission lines above ~500 eV. Because the AURIC code predicts significantly higher fluxes than are observed in both the 505 and 568 eV channels, the treatment of Auger features in the cross sections cannot explain the disagreement.

It is interesting to note that the AURIC code, which uses the highest resolution photoelectron production cross section, systematically overestimates the observed electron fluxes. The irradiance spectra below 6 nm used here are derived from model-dependent distributions of power observed in a broad wavelength region. Figure 2 shows the significant differences in modeled irradiance spectra in this region. Peterson et al. [2012] found that the variability of solar irradiance below 6 nm was not fully captured in any of the irradiance models they considered. We do not have the information to determine if the systematic overestimation of photoelectron fluxes above 600 eV arises from imperfect knowledge of the photoionization cross sections or imperfect knowledge of the solar irradiance spectrum below 6 nm.

4.3.2. Energies Between 20 and 200 eV
In spite of the significant differences in irradiance spectra and photoionization cross sections relevant to energies in the 20 to 200 eV range, the photoelectron spectra calculated with all three codes agree remarkably well with observations. Figure 5 shows that on average and within observational uncertainty, the calculated photoelectron energy spectra between 20 and 200 eV are within 50% of the observations with three exceptions. The exceptions are preflare fluxes calculated using the AURIC/HESSR pair, preflare and postflare fluxes calculated using the STET/HESSR and STET/L3D pair, and postflare fluxes calculated using the KS/L3FR pair. Examination of the highest-energy resolution data in Figure 4 show that the exceptions reflect the systematically different energy responses calculated in the 20 to 200 eV range.

The data/KS model agreement decreases systematically from ~56 eV to over 200 eV (which corresponds to photons with wavelengths between 6 and 17 nm) for all cases examined. These systematic variations with energy are associated with the systematic decrease in magnitude of the photoionization cross section (orange line in Figure 7) below ~30 nm. The response of the STET and AURIC codes from 56 to 200 eV are more complicated. The systematic decrease seen in the data/KS model agreement appears near 200 eV in the preflare STET and AURIC models using the L3D and postflare STET and AURIC models using the L3FR irradiance spectra.

In contrast to the systematic decreases in data/model agreement noted above, there is a systematic increase near 200 eV for the STET and AURIC data/model agreement using the preflare HESSR irradiance and postflare L3F irradiance spectra. The more intense irradiance features near 6 nm in the HESSR and L3F irradiance spectra are strong enough to overcome decreases in the photoionization cross sections.

4.3.3. Energies Below 20 eV
Figure 5 shows that the data/model agreement in the 10–20 eV range is within observational uncertainties for all model/irradiance spectra pairs examined. Data are available for comparison with the models only above ~5 eV, which is the lowest SWEA energy step plus the spacecraft potential. Figure 4 shows that the data/model agreement within observational uncertainties extends to 5 eV for the AURIC code but not the KS and STET codes. Electrons with energies in the 5 eV range can be produced by photons with wavelengths...
near 65 nm, where the cross section for photoionization has many features associated with the production of excited states of CO₂. The AURIC code is routinely used to investigate optical emissions from ionized plasmas and has been extensively validated [Strickland et al., 1999] in this energy/wavelength range.

5. Data-Model Comparison Using Observed CO₂ Densities

The model photoelectron fluxes presented and discussed above were all calculated using the M-GITM model CO₂ density shown in Figure 6. Table 2 shows that the postflare CO₂ densities from the NGIMS instrument and M-GITM agree to within 1%, so postflare electron fluxes are unchanged. The preflare CO₂ densities at the measurement altitude observed by the NGIMS instrument are 11% higher than the M-GITM values.

Xu et al. [2015b] have shown that in collision-dominated regions the flux of high-energy electrons is surprisingly insensitive to neutral density. A test run of the STET code with double the M-GITM density showed a factor of less than 2 increase in the electron flux at 1 eV but essentially no change above 10 eV. Thus, the comparisons between modeled and observed fluxes for the energy bands shown in Figure 5 are not changed when observed CO₂ densities are considered.

6. Conclusion

We examined electron data obtained on successive MAVEN passes with different incident solar EUV and XUV irradiances. We then compared observed and modeled electron spectra based on observed irradiance and CO₂ density. The discussion above shows that in spite of large differences in photoionization cross sections and irradiance spectra incident on Mars, the differences in Martian photoelectron energy spectra calculated with three commonly used codes (i.e., KS, AURIC, and STET) are small compared to the combined uncertainties of observations from the SWEA, NGIMS, and EUVM instruments on the MAVEN spacecraft.

The most significant differences were found for photoelectrons with energies above ~600 eV and below ~5 eV. The Atmospheric Ultraviolet Radiance Integrated Code (AURIC) best agreed with data below ~5 eV. The SuperThermal Electron Transport (STET) code and a two-stream code developed at Kansas University best agreed with data above ~600 eV. Between 200 and 600 eV the lower photoionization cross section used in the KS code results in calculated photoelectron fluxes less than 50% below those observed. We do not have the information to determine if the more than 50% overestimation of photoelectron fluxes above 600 eV by the AURIC code arises from imperfect knowledge of the photoionization cross sections or imperfect knowledge of the solar irradiance spectrum below 6 nm.

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