Comparison of Different Solar Irradiance Models for the Superthermal Electron Transport Model for Mars

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Abstract

As the solar photon fluxes directly control the production of photoelectrons, it is important to examine the influence of different solar irradiance models on the photoelectron fluxes. In this study, we present the implementation of the two recent solar irradiance models, the Flare Irradiance Spectral Model (FISM) and the Heliospheric Environment Solar Spectral Radiation (HESSR) model, to our SuperThermal Electron Transport (STET) model. In addition, we have proposed a new modification to the Hinteregger-81 model. The resultant photoelectron fluxes from the three solar irradiance models, the Hinteregger-81 model, FISM and the HESSR model, are compared and mostly vary within a factor of 2.

Keywords: photoelectron, solar irradiance models, superthermal electron transport, Mars

1. Introduction

Solar electromagnetic irradiance is a major energy source of the planets' upper atmospheres. After photoionizing neutral particles, the remaining en-

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ergy of these solar photon fluxes, especially the extreme ultraviolet (EUV) photons, is mostly carried by photoelectrons. Thus, photoelectrons play an important role in the dynamics and evolution of the planets' upper atmosphere and can cause heating, dissociation and ionization, and excitation (e.g. Schunk and Nagy, 2000). In particular, photoelectrons below 100 eV can efficiently heat the ambient electrons in the ionosphere through Coulomb collision (e.g. Hanson and Johnson, 1961). The ionosphere and thermosphere can be consequently heated through collisions between charged particles and neutral particles.

Various models have been developed to simulate the superthermal electron transport for Mars' space environment (e.g. Mantas and Hanson, 1979; Haider et al., 1992; Seth et al., 2002; Liemohn et al., 2003; Leblanc et al., 2006; Lillis et al., 2008). In particular, the SuperThermal Electron Transport (STET) model (Liemohn et al., 2003) and the Mars Monte Carlo Electron Transport Code (MarMCET) (Lillis et al., 2008) are capable of simulations with non-uniform magnetic fields. This capability is vital to understand the Martian plasma environment because of the existence of strong crustal fields over the southern hemisphere (e.g. Acuña et al., 1998; Brain et al., 2003, 2007; Krymskii et al., 2003; Harnett and Winglee, 2005; Ma et al., 2014).

Solar EUV photon fluxes directly control the photoelectron fluxes (e.g. Banks and Nagy, 1970). Measurements and models of the solar EUV and XUV fluxes are therefore vital to accurately obtain photoelectron fluxes. However, any one solar irradiance model is based on a limited set of observations and has caveats to its applicability and errors on its accuracy. For example, Peterson et al. (2012) compared the Earth observation and the

modeled photoelectron spectra with five different solar irradiance models as the solar energy input and concluded that all the investigated models failed to capture the variability of solar irradiance on the solar rotation time scale. This limitation of observations is especially true at planets other than Earth, where solar irradiance measurements are few. Furthermore, most superthermal electron transport models only use a single solar irradiance model for the specification of this important input parameter. It is useful, then, to systematically examine the influence of using different solar irradiance flux models on the resulting superthermal electron distribution.

For our STET model, one of the mostly widely used solar irradiance modes, the Hinteregger-81 model (Hinteregger et al., 1981), is currently incorporated to calculate solar irradiance. Hinteregger-81 is an empirical model based on the fitting of observations from the Atmospheric Explorer-E (AE-E) and several sounding rockets. However, Woods et al. (2005) found the discrepancy of a factor of a few between the modeled Hinteregger-81 solar fluxes and the observations from Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) Solar Extreme Ultraviolet Experiment (SEE)(Woods et al., 1998). Hence it is necessary to compare the performance of other solar irradiance models' to the Hinteregger-81 model, in the aspect of the resultant photoelectron fluxes.

We have selected two recently developed solar irradiance models to implement into the STET model: the Flare Irradiance Spectral Model (FISM) (Chamberlin et al., 2007, 2008) and the Heliospheric Environment Solar Spectral Radiation (HESSR) model (Fontenla et al., 2009, 2014). We will briefly introduce the models used in this study (section 2), describe the implementa-

tion of the two solar irradiance models (section 3.1), present the comparison of the results of the Hinteregger-81 model, FISM and the HESSR model (section 3.2), and conclude this study in section 4.

2. Methodology

The STET model calculates the superthermal electron distribution function by solving the gyration-averaged Boltzmann kinetic equation along a flux tube in the coordinate system $[t, E, s, \mu]$, where t is time; E is the electron energy in eV; s is the coordinate along the local magnetic field line, and μ is the cosine of the local pitch angle. This multi-stream model was originally developed for the Earth environment (Khazanov et al., 1993; Khazanov and Liemohn, 1995; Liemohn et al., 1997) and then adapted for Mars (Liemohn et al., 2003, 2006). Xu and Liemohn (2015) provides the detailed description of the STET model. In particular, the photoionization and excitation cross sections are from Fox (1991), along with the electron impact cross sections from Sung and Fox (2000). The neutral and ionospheric plasma density profiles are from Mars Thermospheric General Circulation Model (MTGCM) (Bougher et al., 1988, 1994, 2001) for the altitude range of 100-240 km and linearly extrapolated from the logarithm of the two topmost values from MTGCM above 240 km.

The FISM model, an empirical solar irradiance model that is based on more accurate measurements from several instruments on three different satellites (such as TIMED SEE for EUV irradiance data), makes use of six proxies for different wavelengths/bands, treats the solar cycle and solar rotational components separately, and also, in addition the daily component,

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9 includes the solar irradiance variations from both the impulsive and gradual
10 phases of the solar flares.
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13 The HESSR is a semi-empirical model of the Solar Spectral Irradiance
14 (SSI) at planets and a derivative of the Solar EUV Radiation Forecast System
15 (SERFS) model described by Fontenla et al. (2014), which was developed
16 to model the Ultraviolet (UV) SSI at Earth. The SERFS model is based
17 on the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly
18 (AIA) images of the solar disk available since August 2010 that produce
19 daily “masks” of the solar disk that identify a set of 11 chromospheric and
20 coronal features directly observed on the disk. For the application to other
21 planets, i.e. in HESSR, maps of the features on the solar disk are derived
22 from the current and previous solar disk masks. Using these maps, the
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24 solar features are projected to the planets viewing positions to produce daily
25 projected masks at each planet. Then these projected masks are used in the
26 same way as the Earth case to produce planetary UV SSI predictions. The
27 resulting SSI can be produced at any desired resolution, but for practical
28 purposes the planetary data used in this paper is re-binned into 1-nm bins.
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30 When observations are available from other viewpoints in the heliosphere, or
31 helioseismology of the far-side, these data can be used to direct update the
32 maps of features and thereby bring more up to date the state of the solar
33 disk viewed from other planets (Fontenla et al., 2009).
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35 For the HESSR model, the photon fluxes (available wavelength 0.05-
36 160 nm, <http://www.galactitech.net/hessrdata/Mars/Spectra/>) are al-
37 ready in Mars values. For the other solar irradiance models, the modeled
38 solar photon fluxes from both the Hinteregger-81 model and FISM (available
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wavelength 0-190 nm, <http://lasp.colorado.edu/lisird/fism/>) are currently Earth values, which are then scaled by the relative distances of the two planets from the Sun and interpolated according to the Mars-Sun-Earth angle, to obtain Mars values.

3. Results

The neutral densities (including five species, O, O₂, N₂, CO₂, CO), ionospheric density and temperature profiles based on MTGCM are shown in Figure 1a. The MTGCM run was at an Ls of 90 degrees with an Earth F_{10.7} of 100 sfu (1 sfu = 10⁻²² W/(m² Hz)). The magnetic field line configuration is a symmetric field line, as shown in Figure 1b-d. The distance step size of the field line is 5 km below 200 km to well resolve the ionosphere and 10 km above. A total of 20 pitch angle grid points for pitch angle 0–90° are used for electron fluxes flowing along the magnetic field direction and the same pitch angle setup for the opposite flowing electrons. In addition, a non-constant energy grid size is set up as follows: 1 eV for energy below 40 eV, 2 eV for 40-200 eV, and 4 eV for energy above 200 eV. All the runs in this study are steady-state by setting a large time step of 10⁵ s, so that the time derivative term (see equation (1) in (Xu and Liemohn, 2015)) is mostly negligible. The simulation is considered to be converged as $|\psi - \psi_{last}|/\psi < 0.02$, where ψ and ψ_{last} are the electron flux at the current time step and the last time step at every location in the $E - s - \mu$ grid.

In this study, we have chosen July 13th, 2014 for the reference of the solar irradiance models. For the Hinteregger-81 model, the inputs are F_{10.7} = 127 sfu and 81-day average index F_{10.7a} = 135 sfu. As both the Hinteregger-81

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138 model and the HESSR model predict daily solar photon fluxes, we only use
139 the daily component of FISM for this study, rather than including the high-
140 time-resolution flare component, to most appropriately compare the influence
141 of three models' daily predictions on the photoelectron fluxes. In addition,
142 there were only several very minor flares (class C) on July 13th, 2014 so that
143 the daily component is an adequate representation of the total solar flux.
144 Both FISM and HESSR use observations from July 13th, 2014 as inputs to
145 drive the models.

146 *3.1. Implementation of New Solar EUV Models*

147 The absorption and photoionization cross sections in the STET model
148 are in the same resolution as the Hinteregger-81 model, 41 wavebands and
149 18 single spectral lines for strong emission lines, with a resolution of < 1
150 nm below 3.2 nm, then 1.8 nm for 3.2-5 nm and a resolution of 5 nm for the
151 wavelength range 5–175 nm (see more detailed resolution information in Ta-
152 ble 1 of Heroux and Hinteregger (1978)). Both FISM and the HESSR model
153 data used in this paper, however, are currently of a bin size of 1 nm. To
154 avoid confusion, here we denote the resolution of the Hinteregger-81 model
155 as “the uneven resolution”, in contrast to the 1 nm resolution of the two new
156 solar irradiance models. Hence, we have constructed three ways to incorpo-
157 rate the two new models. The most straight forward way (method 1) is to
158 integrate the solar photon fluxes from the two new models into the uneven
159 resolution for long wavelengths and linearly interpolate for wavelengths be-
160 low 3.2 nm, where the Hinteregger-81 model has finer resolution than 1 nm.
161 Figure 2a shows the comparison of the solar photon fluxes from FISM (dark
162 blue) and the HESSR model (red) in 1 nm resolution while the integrated

versions of FISM (dark blue) and the HESSR model (red) in the uneven resolution are shown in Figure 2b, accompanied with the solar irradiance from the Hinteregger-81 model (black) as a comparison.

However, method 1 results in the loss of the finer wavelength resolution above 3.2 nm. Therefore, instead of integrating solar irradiance, the other two methods are to linearly interpolate the absorption and photoionization cross sections to 1 nm resolution. It is only suitable to implement this way when the cross sections are smooth. As shown in Figure 2c and 2d, both the absorption and photoionization cross sections, crosses for the uneven resolution and solid lines for the interpolated 1 nm resolution, are rather smooth below 70 nm but quite spiky above. Considering 70 nm (~ 18 eV in energy per photon) is about the wavelength threshold to photoionize neutrals, it is appropriate to interpolate the cross sections. The difference between the two methods lies in how to deal with the 18 single spectral lines, as indicated by the red/blue crosses in Figure 2a. The second method (method 2) is to first interpolate the cross sections for the 41 wavebands into 175 bins with 1-nm resolution. Then for those 18 1-nm bins that contain the single spectral lines, the cross sections obtained from the waveband interpolation will be replaced by the original cross sections of the corresponding single spectral lines.

The third method (method 3) is to interpolate the cross sections for the 41 wavebands into 175 bins with 1-nm resolution and, instead of replacing, add the extra 18 single spectral lines. In other words, the third method has 18 more bins (with the same upper and lower bound for each bin) than does the method 2. The photon fluxes for the extra 18 single spectral lines

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188 are from the 1-nm bins that contain the 18 single spectral lines. The third
189 method resembles the way the Hinteregger-81 model calculates the solar pho-
190 ton fluxes, adding extra photon fluxes from the single-spectral-line bins into
191 the fluxes from the wavebands.

192 To briefly summarize, for both FISM and the HESSR model, there are
193 two fundamental ways to incorporate them into the STET model: (1) in-
194 tegrating and interpolating the solar irradiance to fit the absorption and
195 photoionization cross sections in uneven resolution (method 1); (2) interpo-
196 lating the absorption and photoionization cross sections in 1 nm resolution
197 (method 2 and method 3). Method 2 and method 3 differ in the treatment
198 of the single spectral lines.

199 3.1.1. FISM

200 The comparison of FISM implemented in these three methods is demon-
201 strated in Figure 3. The upper panel of Figure 3 shows the omni-directional
202 photoelectron fluxes against energy at 200 km, just above the collisional iono-
203 sphere. The solid line is for FISM in the uneven resolution, the dashed line
204 for method 2 and the dotted line for method 3, the latter two in 1-nm resolu-
205 tion. All three energy spectra are mostly on top of each other. A noticeable
206 difference between the two resolutions is the steeper drop of electron fluxes
207 for the uneven resolution near 60-70 eV due to the coarser wavelength res-
208 olution above 3.2 nm. In contrast, the 1-nm resolution results in a broader
209 decrease of fluxes from approximately 50 to 70 eV. A more quantitative com-
210 parison is shown in the lower panel of Figure 3 where the photoelectron fluxes
211 generated by FISM using the absorption and photoionization cross sections
212 at 1-nm resolution are ratioed relative to the fluxes of the uneven resolution

213 FISM, by dividing the dashed and dotted lines in the upper panel by the
 214 solid line. The difference **between** the two resolutions is within a factor of
 215 3. The discrepancy between method 2 and 3 is seen at energy below 40 eV.
 216 Without the extra single-spectral-line bins, the dashed line is off the solid
 217 line, i.e. in the uneven resolution, by a factor less than 2. The dotted line,
 218 however, is closer to the solid line, as both the method 1 and 3 have ad-
 219 ditional extra photon fluxes from the single-spectral-line bins. However, it
 220 is not yet clear if the additional fluxes from these single-spectral-line bins
 221 will result in overestimated photoelectron fluxes for the low energy range. In
 222 other words, it is inappropriate to conclude which method is better without
 223 a comprehensive data-model comparison study.

224 3.1.2. *HESSR Model*

225 Similarly, Figure 4, in the same format as Figure 3, shows how the three
 226 methods **used** to incorporate the HESSR model affect the photoelectron en-
 227 ergy spectra. Again, the resultant photoelectron fluxes from the three meth-
 228 ods vary within a factor of around **4**. The lower panel of Figure 4 mostly
 229 resembles the lower panel of Figure 3 below 100 eV. The noticeable feature
 230 for the HESSR model is that the second and third methods, (dashed and
 231 dotted lines), result **in** more variance from the first method above 100 eV,
 232 compared to the FISM case. It is due to the more dramatic decrease of the
 233 solar irradiance from 3 nm to 2 nm for the HESSR model, compared to FISM,
 234 as the HESSR model tends to predict much lower solar irradiance below 2
 235 nm than FISM. As a result, the interpolation of the HESSR solar irradiance
 236 to the uneven resolution at short wavelengths brings more variance to the
 237 high-energy photoelectron fluxes.

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238 As the only discrepancy between method 2 and 3 is below 40 eV, here-
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11 inafter we will only show the results of the method 2 to demonstrate cases
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13 of 1-nm resolution.
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15 16 3.2. Comparison of the Solar EUV Models 17

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19 In this section, we will compare the photoelectron fluxes with different
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21 solar irradiance models as input, as shown in Figure 5. The left column
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23 demonstrates the comparison of the various models in the uneven resolution
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25 while the right column shows the results of FISM and the HESSR model
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27 with the model absorption and photoionization cross sections interpolated
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29 to 1-nm resolution, with the Hinteregger-81 model for comparison. Again,
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31 the upper panels are for omni-directional photoelectron fluxes against energy
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33 at 200 km and the lower panels for the fluxes relative to the Hinteregger-81
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35 model case. In each panel, the Hinteregger-81 model case is in black, FISM
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37 in green, and the HESSR model in red.
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39 3.2.1. Comparison of Photoelectron Fluxes 40

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42 For the uneven resolution (left column of Figure 5), the results of FISM
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44 and the HESSR model generally agree well for the energy range 40-300 eV,
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46 within a factor 2. Below 40 eV, though modeled photoelectron fluxes fluctu-
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48 ate dramatically, the photoelectron fluxes from the two newer solar irradiance
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50 models are generally within a factor of 2 as well. Above 300 eV, the resultant
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52 electron fluxes from the HESSR model are about half of that from FISM.
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55 The right column of Figure 5, for absorption and photoionization cross
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57 sections being interpolated to 1-nm resolution, shows similar features de-
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59 scribed above. However, it is noticeable that the resultant photoelectron
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fluxes from the HESSR model is much lower than FISM, around 10-20 %, as the HESSR model tends to predict much lower solar irradiance below 2 nm than FISM. Also, the energy spectra resulting from the two new solar irradiance models, as shown in the right upper panel, decrease more smoothly from 50 eV to 300 eV, while for the Hinteregger-81 model case, the decrease is semi-staircase (likely due to the coarser wavelength resolution above 3.2 nm).

3.2.2. Modifications to Hinteregger-81 Model

From Figure 5, it is easy to see that the Hinteregger-81 model leads to much lower photoelectron fluxes than the other two solar irradiance models, except for the HESSR model at high energy range. Solomon et al. (2001) concluded that the solar photon fluxes from the Hinteregger-81 model needed to be multiplied by a factor of 4 below 25 nm to match the observation. The Hinteregger-81 model with this modification is shown in aqua in Figure 5. While this modification makes the Hinteregger-81 model case match much better with FISM above 360 eV in the uneven resolution (left column), it results in higher photoelectron fluxes by a factor of around 2 from 40 eV to 360 eV than both FISM and HESSR cases. Xu and Liemohn (2015) also suggested that the correction of Solomon et al. (2001) seems to extend to longer wavelengths than necessary through their data-model comparison. The right column of Figure 5 shows this similar trend, better agreement with FISM above 230 eV but overshoot in the energy range of 40-230 eV compared to the two newer models.

Woods et al. (2005) found that the modeled solar photon fluxes from the Hinteregger-81 model was 50% higher in the 50-75 nm range than the SEE

287 measurement from February 2002 to mid-2004 and that the observation was
 288 70% higher than the modeled solar fluxes in the 5-25 nm range. Therefore,
 289 a simple new modification to the Hinteregger-81 model is to combine the
 290 findings from both studies, multiplying the modeled solar fluxes from the
 291 Hinteregger-81 model by 2/3 in the 50-75 nm range, by 1.7 in the 3.2-25
 292 nm range, and by 4 below 3.2 nm. The choice of 3.2 nm cutoff instead of 5
 293 nm is due to the better agreement with the other two models. The resultant
 294 photoelectron fluxes with this new modification are shown in blue in Figure 5
 295 and agree quite well with the newer models for energies between 40 eV to
 296 300 eV and with FISM above 300 eV. This new modification does lead to
 297 lower photoelectron fluxes below 40 eV than the Solomon modification and
 298 also the other two models.

299 4. Discussion and Conclusions

300 Both FISM and the HESSR model are improved solar spectral models
 301 which can be used to simulate the photoelectron fluxes at Mars. Our STET
 302 model currently includes the Hinteregger-81 model description of the photon
 303 fluxes. However, the Hinteregger-81 model contains a coarse wavelength
 304 resolution and we examine how the inclusion of the improved wavelength
 305 resolution of FISM and the HESSR model affects how the photoelectron
 306 fluxes predicted by STET would be altered.

307 In the previous sections, we have described how to incorporate FISM and
 308 the HESSR model into our STET model in detail. Due to the different wave-
 309 length resolutions of the absorption and photoionization cross sections and
 310 the two new solar irradiance models, three methods have been constructed to

integrate the new models to STET. The first method is to simply integrate and linearly interpolate the FISM and the HESSR model into the uneven resolution, i.e. the Hinteregger-81 resolution. The second and third methods are to interpolate the cross sections, instead, and handle strong emission lines differently. The resultant omni-directional photoelectron fluxes of the three methods generally agree well with each other, varying within a factor of 3.

In this study, we have also proposed a new modification for the Hinteregger-81 model. While Solomon et al. (2001) provided a good correction of the Hinteregger-81 model for short wavelengths, it does introduce higher photoelectron fluxes in the energy range 40-360 eV. This new modification combines the finding of Solomon et al. (2001) and Woods et al. (2005), leading to a better agreement with the other two models.

Finally, with the modifications, the resultant omni-directional fluxes of the three solar irradiance models, the Hinteregger-81 model, FISM, and the HESSR model, mostly vary within a factor of 2. However, the HESSR model does not include flares and therefore maybe somewhat lower than the daily averaged SSI at wavelengths below 2 nm, which leads to lower photoelectron fluxes above 300 eV. The variation among three models is decent enough to validate the three models but also leaves room to further discriminate which EUV model delivers the better performance. However, to determine which solar irradiance model prevails requires an extensive data-model comparison study. The Analyzer of Space Plasma and Energetic Atoms (ASPERA-3) experiment Electron Spectrometer (ELS) instrument (Barabash et al., 2006) from Mars Express (MEx) provides a very fine resolution ($dE/E=8\%$) for electron measurements at energies below 100 eV. These measurements could

also be utilized to compare the solar irradiance models. In addition, with the arrival of the Mars Atmosphere and Volatile Evolution (MAVEN) at Mars, the new superthermal electron data from the spacecraft should give more insight into this issue. Furthermore, the instrument LPW/EUV onboard MAVEN provides direct measurements at several wavelengths (0-7 nm, 171 nm, and 121.6 nm) and will vastly improve our understanding of solar irradiance at Mars. In fact, these measurements will be used to drive FISM to predict full solar irradiance spectra.

In the near future, the HESSR model with the inclusion of far-side observation of the Sun and the FISM based on observations from MAVEN will provide much more accurate prediction of the solar irradiance spectra at Mars than the Hinteregger-81 model, especially when Earth and Mars are on the opposite sides of the Sun. With these improved solar irradiance models, our STET model is consequently able to deliver better simulations of superthermal electron transport at Mars.

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Figure 1: (a) Neutral densities, thermal electron density and neutral temperature of Mars to be used in the calculations that follow, against altitude. These values are from MTGCM for the altitude range of 100-240 km and linearly extrapolated from the logarithm of the two topmost values from MTGCM above 240 km; (b) B field line altitudes against distance s; (c) B field strength against altitude; (d) B field strength against distance s.

Figure 2: (a) Solar fluxes from FISM (blue) and HESSR model (red) against wavelength, in 1 nm resolution. The blue and red crosses indicate the wavelengths of the 18 single spectral lines. (b) Solar fluxes from Hinteregger-81 model (black), FISM (blue), and HESSR model (red) against wavelength, in the uneven resolution. Absorption cross section (c) and photoionization cross section (d) against wavelength; crosses for the uneven resolution and solid lines for the interpolated 1 nm resolution.

Figure 3: The upper panel is the omni-directional flux against energy. The three lines are for different ways to implement FISM, the solid line for method 1, integrating FISM photon fluxes to the uneven resolution, the dashed line for method 2, FISM and absorption and photoionization cross sections interpolated to 1 nm resolution, and the dotted line for method 3, FISM and absorption and photoionization cross sections interpolated to 1 nm resolution with additional single-spectral-line values. The lower panel is the relative omni-directional fluxes of three methods against energy, i.e., the dashed and dotted lines in the upper panel divided by the solid line.

Figure 4: The same format as Figure 3. This figure shows the comparison of the three methods to implement the HESSR model.

Figure 5: The upper two panels are the omni-directional flux with different EUV models against energy. The black line is for the Hinteregger-81 model without modification, aqua for Hinteregger-81 with the Solomon modification, blue for Hinteregger-81 with the new modification, green for FISM, red for HESSR model. The lower two panels are the relative omni-directional photoelectron fluxes against energy, i.e., other color lines divided by the black line in the upper panel. The left column is in the uneven resolution while the right column is for FISM and the HESSR model implemented with method 2.