1 (2)

Solar wind interaction with the Martian upper atmosphere: Crustal field orientation, solar cycle and seasonal variations

Chuanfei Dong,[1] Stephen W. Bougher,[1] Yingjuan Ma,[2] Gabor Toth,[1] Yuni

Lee,[1] Andrew F. Nagy,[1] Valeriy Tenishev,[1] Dave J. Pawlowski,[3] Michael R.

Combi,[1] and Dalal Najib[4]

———

Corresponding author: C. F. Dong, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, Michigan, USA. (dcfy@umich.edu)

[1]Department of Atmospheric, Oceanic

and Space Sciences, University of Michigan,

Ann Arbor, Michigan, USA.

[2]Department of Earth and Space Sciences,

UCLA, Los Angeles, California, USA.

[3]Department of Physics and Astronomy,

Eastern Michigan University, Ypsilanti,

Michigan, USA.

[4]National Academy of Sciences,

Washington, D.C., USA.

D R A F T   August 12, 2015, 6:02pm   D R A F T

5 **Abstract.**   A comprehensive study of the solar wind interaction with the

6 Martian upper atmosphere is presented. Three global models: the 3-D Mars

7 multi-fluid Block Adaptive Tree Solar-wind Roe Upwind Scheme (BATS-R-

8 US) MHD code (MF-MHD), the 3-D Mars Global Ionosphere Thermosphere

9 Model (M-GITM) and the Mars exosphere Monte Carlo model Adaptive Mesh

10 Particle Simulator (M-AMPS) were used in this study. These models are one-

11 way coupled, i.e., the MF-MHD model uses the 3-D neutral inputs from M-

12 GITM and the 3-D hot oxygen corona distribution from M-AMPS. By adopt-

13 ing this one-way coupling approach, the Martian upper atmosphere ion es-

14 cape rates are investigated in detail with the combined variations of crustal

15 field orientation, solar cycle and Martian seasonal conditions.

16   The calculated ion escape rates are compared with Mars Express (MEX)

17 observational data and show reasonable agreement. The variations in solar

18 cycles and seasons can affect the ion loss by a factor of ~ 3.3 and ~ 1.3, re-

19 spectively. The crustal magnetic field has a shielding effect to protect Mars

20 from solar wind interaction, and this effect is the strongest for perihelion con-

21 ditions, with the crustal field facing the Sun. Furthermore, the fraction of

22 cold escaping heavy ionospheric molecular ions $[(O_2^+$ and/or $CO_2^+)/$Total$]$ are

23 inversely proportional to the fraction of the escaping (ionospheric and corona)

24 atomic ion $[O^+/$Total$]$, whereas O_2^+ and CO_2^+ ion escape fractions show a pos-

25 itive linear correlation since both ion species are ionospheric ions that fol-

26 low the same escaping path.

1. Introduction

The Sun has a powerful influence on planetary atmospheres. Annual changes in temperature on a planet are caused by a combination of two factors: axial tilt and variations in the distance from the Sun. On Earth, the axial tilt determines nearly all of the annual variations, because Earth's orbit is nearly circular. Mars, however, has the highest orbital eccentricity of any planet except Mercury; the distance from the Sun to Mars varies approximately from 1.38 AU to 1.66 AU over a Martian year. This large variation, combined with an axial tilt (25.19°) slightly greater than Earth's (23.4°), gives rise to seasonal variations far greater than those we experience even in the coldest areas on our own planet [*de Pater and Lissauer*, 2010]. Furthermore, Mars has no global intrinsic dipole magnetic field; instead, it has a crustal magnetic field, which was first discovered by the Mars Global Surveyor spacecraft (MGS) [*Acuña et al.*, 1999]. The crustal fields, B_c, are distributed about the surface of the planet in a very inhomogeneous manner, which plays an important role in the process of solar wind planet interaction. The strongest crustal sources are located at latitudes poleward of 30° S and at longitudes between 120° − 240° E [*Acuña et al.*, 1999].

Atmospheric dynamics and chemistry are greatly affected by temperature, suggesting that the entire Mars atmosphere is an integrated system that must be treated as a whole from the ground to the exobase (∼ 0 to 250 km) [*Bougher et al.*, 2015]. In fact, strong coupling processes are known to link the Mars lower to upper atmospheres [e.g., *Bougher et al.*, 2014]. These processes are crucial to be quantified in order to reliably predict upper atmosphere densities, temperatures, winds, planetary waves (e.g., tides and gravity

waves) over various timescales (e.g. solar cycle, seasonal, and diurnal). Three-dimensional "whole atmosphere" models are ultimately required to capture these coupling processes (e.g., thermal, chemical, dynamical) throughout the entire Mars atmosphere. The 3-D Mars Global Ionosphere Thermosphere Model (M-GITM) [*Bougher et al.*, 2015] is such a model that can generate a relatively realistic Martian atmosphere with detailed structures that incorporates the effects of solar cycle and seasonal variations. Cold neutral atoms and molecules in this paper refer to the thermal particles, and hot oxygen refers to those from dissociative recombination of O_2^+. Basically, the hot oxygen has a thermal speed larger than the local background thermal speed (calculated based on M-GITM thermospheric profile [*Bougher et al.*, 2015]), indicating the scale height of hot oxygen is larger than that of the cold oxygen (e.g., Figures 1 and 2 in *Ma et al.* [2004]). However, the hot oxygen can be converted to the thermal oxygen via collisions with other background cold neutral species before it escapes to interplanetary space [*Lee et al.*, 2013]. It is noteworthy that when we mention the cold heavy ionospheric molecular/atomic ions, it refers to those ionized from the cold molecular/atomic neutrals. However, these ions can be accelerated to relatively high energy during their escape.

The weak gravity of Mars allows an extended corona of hot species to be present [*Valeille et al.*, 2009]. Among all the chemical reactions, dissociative recombination of O_2^+ (O_2^+ + e $\longrightarrow$ O + O + energy) is the most important one, which is responsible for most of the production of dayside exospheric hot atomic oxygen. Besides, the sputtering caused by pickup ion (e.g., O^+) collisions with the Martian atmospheric neutral species is also an important source for the hot corona [*Johnson and Luhmann*, 1998]. There are hot hydrogen and carbon coronae as well [*Lee et al.*, 2014a].

71   The cold exospheric component (e.g., see *Ma et al.* [2004] Figures 1 and 2) also plays

72 an important role in the solar wind interaction with the Martian upper atmosphere, espe-

73 cially below 600 km [*Feldman et al.*, 2011]. In order to reproduce a realistic asymmetric

74 corona of hot species from observations, a 3-D global kinetic exosphere model is required,

75 especially above the exobase (Knudsen number, $K_n \approx 1$) where the fluid assumption usu-

76 ally fails [*Lee et al.*, 2013]. One such model is the Mars exosphere Monte Carlo model

77 Adaptive Mesh Particle Simulator (M-AMPS) [*Tenishev and Combi*, 2008; *Lee et al.*,

78 2013, 2014a, b], which can generate a 3-D hot (e.g., oxygen and carbon) corona with

79 detailed asymmetric structure. In order to capture these 3-D asymmetries, 3-D thermo-

80 sphere/ionosphere inputs from a validated ground-to-exobase atmospheric model (e.g.,

81 M-GITM) are essential (see Figure 1 for more details).

82   Over the last thirty years, a series of spacecrafts with plasma instrumentation have been

83 sent to Mars, (e.g., Phobos 2, Mars Global Surveyor (MGS), and Mars Express (MEX)

84 missions). The recent NASA Mars Atmosphere and Volatile EvolutioN (MAVEN) mission

85 was launched on November 18, 2013, and successfully entered an orbit around Mars on

86 September 21, 2014. MAVEN will explore the Mars upper atmosphere, ionosphere and

87 interactions with the solar EUV radiation and solar wind environment, and determine the

88 role that loss of volatiles to space has played through time. Recently, the study of the

89 solar wind interaction with Mars upper atmosphere/ionosphere has received a great deal

90 of attention, especially the investigation of ion escape rates due to its potential impact

91 on the long-term evolution of Mars atmosphere (e.g., loss of water) over its history. A

92 number of papers reporting on the measurement of ion escape rates by the ASPERA-3

93 instrument on the Mars Express spacecraft have also been published [e.g., *Barabash et al.*,

2007; *Lundin et al.*, 2008, 2009, 2013; *Nilsson et al.*, 2011]. In *Lundin et al.* [2013], they reported that the average heavy ion escape rate is increased by a factor of ~ 10, from $\sim 1 \times 10^{24}$ s^{-1} (solar minimum) to $\sim 1 \times 10^{25}$ s^{-1} (solar maximum). On the other hand, both *Verigin et al.* [1991] and *Nilsson et al.* [2011] suggested that high solar activity leads to ~ 2.5 times higher ion escape rate than the low solar activity result.

It is difficult to accurately estimate ion escape rates from spacecraft data due to the complex geometry of loss regions around Mars. Thus the use of global simulations is necessary. Various plasma models based on different assumptions, i.e., test particle model [*Fang et al.*, 2010; *Curry et al.*, 2013, 2014, 2015], multi-species MHD model [*Ma et al.*, 2004; *Ma and Nagy*, 2007; *Ma et al.*, 2014], multi-fluid MHD model [*Harnett and Winglee*, 2006; *Najib et al.*, 2011; *Riousset et al.*, 2013, 2014; *Dong et al.*, 2014] and kinetic hybrid model [*Modolo et al.*, 2012; *Brecht and Ledvina*, 2014a] have been used to simulate the solar wind interaction with the Martian upper atmosphere and calculate the associated ion escape rates. An ongoing International Space Studies Institute effort focused upon the global models and measurements of the Martian plasma environment being led by Prof. David Brain at the University of Colorado, Boulder, CO [*Brain et al.*, 2010, 2012] allows intercomparison of these multidimensional plasma codes, which will benefit the entire community. However, there have been no systematic studies on the effects of crustal field orientation, solar cycle, and season on the Martian upper atmosphere ion escape by using the variable 3-D cold neutral thermosphere and hot oxygen corona as inputs in a plasma code.

In the present work, we study the solar wind interaction with the Martian upper atmosphere by using a one-way coupling of three comprehensive 3-D models, i.e., the M-GITM

117 thermosphere-ionosphere model outputs (i.e., neutral atmosphere temperatures T_n, neu-

118 tral densities n_O, n_{CO_2}, and photoionization frequencies I_O, I_{CO_2}) and the M-AMPS hot

119 atomic oxygen corona densities ($n_{O_{hot}}$) are used as inputs for the BATS-R-US Mars multi-

120 fluid MHD (MF-MHD) model (see Figure 1 for the one-way coupling framework). The

121 MF-MHD code solves separate continuity, momentum and energy equations for each ion

122 species [*Powell et al.*, 1999; *Glocer et al.*, 2009; *Najib et al.*, 2011; *Tóth et al.*, 2012; *Dong*

123 *et al.*, 2014]. Please refer to *Lee et al.* [2013, 2014a, b] for the detailed study of one-way

124 coupling between M-GITM and M-AMPS (as indicated by the grey arrow in Figure 1),

125 i.e., M-GITM provides neutral atmosphere background as an input into the M-AMPS

126 exosphere model. These calculations are carried out for twenty-two cases with combina-

127 tions of different crustal field orientations (four cases without crustal field), solar cycle

128 and Martian seasonal conditions.

129   The rest of this paper is organized as follows. In Section 2, three models are briefly

130 introduced together with the one-way coupling approach depicted in more detail. In

131 Section 3, simulation results are presented and discussed based on the comparisons of 22

132 selected cases. In the last section, conclusions are summarized.

2. Model Descriptions

133   In this section, we will briefly introduce the Mars Global Ionosphere Thermosphere

134 Model (M-GITM) [*Bougher et al.*, 2015], the Mars exosphere Monte Carlo model Adaptive

135 Mesh Particle Simulator (M-AMPS) [*Lee et al.*, 2013, 2014a, b], and the 3-D BATS-R-US

136 Mars multi-fluid MHD (MF-MHD) model [*Najib et al.*, 2011; *Dong et al.*, 2014]. All these

137 models are being used to generate a model library of simulated outputs for the MAVEN

138 mission (2014-2016).

2.1. Mars Global Ionosphere Thermosphere Model (M-GITM)

Mars Global Ionosphere Thermosphere Model (M-GITM) [*Bougher et al.*, 2015] is a 3-D whole atmosphere code that captures both the Mars lower atmosphere and its thermosphere-ionosphere. The applied domain of this model is 0–250 km (ground-to-exobase). Lower, middle, and upper atmosphere processes are included, based in part upon formulations used in previous lower atmosphere (NASA AMES Mars General Circulation Model [e.g., *Haberle et al.*, 1999]) and upper atmosphere (NCAR Mars Thermospheric General Circulation Model [e.g., *Bougher et al.*, 2000]) models. The typical horizontal grid resolution of M-GITM is $5° \times 5°$ (latitude-longitude) and the vertical coordinate is Δz=2.5 km ($\sim$ 0.25 scale height). This model can calculate the neutral global fields including the temperatures (T_n), and the neutral wind velocities (U_n, V_n, W_n), where the vertical velocity is calculated explicitly for each species. The major neutral species are O, O_2, CO_2, CO, N_2, Ar, and the minor neutral species, $N(^4S)$, $N(^2D)$, NO, He and H_2, will be included soon. The major ions are CO_2^+, O^+, O_2^+, N_2^+, NO^+, which are calculated assuming photochemical equilibrium. Sub-cycling is used for ion-neutral chemistry. Due to the relatively large scale height, hydrogen can only be calculated self-consistently by implementing the two-way coupling between the M-GITM and the M-AMPS models. Therefore, currently M-GITM does not include the calculation of hydrogen. There is no hydrostatic assumption in this model, thus it can deal with large vertical velocities [*Ridley et al.*, 2006; *Deng et al.*, 2008]. It is noteworthy that the previous Mars Thermospheric General Circulation Model (M-TGCM) is based on the hydrostatic assumption [*Bougher et al.*, 2000, 2006], and thus cannot deal with large vertical winds appropriately,

160 especially when experiencing extreme events, such as coronal mass ejections (CMEs) and

161 solar energetic particles (SEPs) heating.

162   Detailed M-GITM simulations have been conducted over the past few years, spanning

163 various seasonal, solar cycle, and dust conditions [*Bougher et al.*, 2015]. Model validation

164 thus far has focused upon simulations for solar longitude Ls = 90, 180, and 270 for both

165 solar minimum (F10.7 = 70) and solar maximum (F10.7 = 200) conditions. The solar

166 longitude, Ls, is the Mars-Sun angle, measured from the northern hemisphere spring

167 equinox, where Ls=0. Specific studies compare M-GITM simulated temperatures and

168 neutral/ion densities against: (a) in-situ Viking 1 descent measurements for aphelion solar

169 minimum conditions, and (b) very limited Mariner 6-7 flyby measurements for perihelion

170 solar maximum conditions (see *Bougher et al.* [2015] for more details).

171   Figure 2 illustrates the CO_2 and O densities on a sphere of altitude 220 km for these

172 two extreme conditions. Interestingly, great day-night side asymmetry and detailed local

173 structure are clearly shown in these four density contour plots, demonstrating the im-

174 portance of adopting 3-D M-GITM neutral outputs. Besides, two coordinate systems are

175 shown in Figure 2: the Geographic (GEO) and the Mars-centered Solar Orbital (MSO)

176 coordinate systems. These plots are shown on a 2-D spherical surface with the rotation

177 axis parallel to both $x - z$ plane (in MSO coordinates) and the plane of the paper, where

178 the subsolar point is highlighted in each plot. Clearly, there is an angle of 25.19 degrees

179 between two z axes due to the axial tilt.

2.2. Mars Adaptive Mesh Particle Simulator (M-AMPS) model

180   The University of Michigan Adaptive Mesh Particle Simulator (AMPS) code was first

181 developed to solve the Boltzmann equation of the gas flow in the coma of a comet [*Tenishev*

182 *and Combi*, 2008]. The AMPS code is developed within the framework of the Direct

183 Simulation Monte Carlo (DSMC) method [*Bird*, 1994], which employs a stochastic solver

184 for both the linear and nonlinear Boltzmann equations. As a standard numerical method

185 today, the DSMC method can represent the collisional dynamics of a finite number of

186 model particles in a rarefied gas flow regime, such as Mars upper atmosphere. Instead

187 of solving the intractable Boltzmann equation, AMPS simulates the ensemble of model

188 particles and captures the physics of the distribution of gas species in tenuous upper

189 atmospheres, where the transitions from a local thermodynamic equilibrium (LTE) region

190 to a non-LTE region occur. To model the Martian hot atomic coronae, M-AMPS was run

191 as a test-particle Monte Carlo model with a stationary background atmosphere supplied by

192 M-GITM (as indicated by the dashed line in Figure 1), completing the one-way coupling

193 framework [*Lee et al.*, 2013, 2014a, b]. Each hot particle in this coupling framework travels

194 within the influence of the planet's gravitational field and collides with background species

195 from M-GITM before escaping to space or being thermalized in the thermosphere. The

196 nominal cell size is about 60 km at the lower boundary of the computational domain, and

197 the maximum cell size is determined by the designated upper boundary of the domain.

198 M-AMPS includes a data table, which keeps all the information from M-GTIM. All the

199 macro-particles in M-AMPS are initialized based on the thermospheric profile in the data

200 table [*Lee et al.*, 2014a, b]. The collision frequencies between different particle species are

201 also evaluated based upon the thermospheric information stored in the data table. The

202 computational domain extends from 100 km above the Martian surface to 5 R_M, where

203 R_M is the radius of Mars ($\sim$ 3396 km).

₂₀₄   Recently, *Lee et al.* [2013, 2014a, b] have successfully finished the one-way coupling

₂₀₅ between M-AMPS and M-GITM (see Figure 1). This coupling approach has been used to

₂₀₆ calculate both the Martian exosphere hot atomic carbon and oxygen coronae [*Lee et al.*,

₂₀₇ 2013, 2014a, b]. Figure 3 shows the hot atomic oxygen number density distribution in

₂₀₈ a logarithmic scale from the 3-D M-AMPS code. The upper panel shows the autumnal

₂₀₉ equinox solar minimum (AEQUMIN, left) and maximum (AEQUMAX, right) conditions

₂₁₀ and the bottom illustrates aphelion solar minimum (APHMIN, left) and perihelion solar

₂₁₁ maximum (PERMAX, right) conditions.

₂₁₂   By comparing these four cases, the hot atomic oxygen corona is the most extensive

₂₁₃ and has the highest O_{hot} abundance for the PERMAX conditions, followed by the AE-

₂₁₄ QUMAX case; the hot atomic oxygen corona for the APHMIN conditions is the weakest.

₂₁₅ Furthermore, all these plots clearly show the asymmetric features of the hot atomic oxy-

₂₁₆ gen distribution, indicating that in order to accurately calculate the ion escape rate, it is

₂₁₇ essential to adopt the 3-D hot oxygen corona in a plasma code.

2.3. BATS-R-US Mars multi-fluid MHD (MF-MHD) model

₂₁₈   The University of Michigan 3-D BATS-R-US multi-fluid MHD (MF-MHD) model was

₂₁₉ initially developed for Earth [*Powell et al.*, 1999; *Glocer et al.*, 2009; *Tóth et al.*, 2012] and

₂₂₀ later it was developed for studies of Mars [*Najib et al.*, 2011; *Dong et al.*, 2014]. The Mars

₂₂₁ MF-MHD model solves separate continuity, momentum and energy equations for the four

₂₂₂ ion fluids H^+, O^+, O_2^+, CO_2^+. Although the multi-species MHD (MS-MHD) model solves

₂₂₃ separate ion continuity equations, it only solves one momentum and one energy equations

₂₂₄ for different ion species [*Ma et al.*, 2004]. Technically speaking, the MF-MHD model is

₂₂₅ more complete than the MS-MHD code [*Ma et al.*, 2004; *Ma and Nagy*, 2007] because

²²⁶ it can better simulate the solar wind planet interaction by considering the dynamics of

²²⁷ individual ion species. The MS-MHD model, however, is computationally much cheaper

²²⁸ than the MF-MHD model. In order to capture the dynamics of individual ion species, we

²²⁹ adopt the MF-MHD model.

²³⁰ Different from the Earth version, the Mars MF-MHD model contains an ionosphere

²³¹ and thus the lower boundary (i.e., the spherical surface with the lowest altitude in the

²³² simulation domain) was extended down to 100 km above the Martian surface. Detailed

²³³ ionospheric chemistry is included, i.e., charge exchange, photoionization and electron im-

²³⁴ pact ionization. In order to calculate the latter, the model assumes that the electron

²³⁵ temperature is half of the calculated plasma temperature and uses the ionization rates

²³⁶ given by *Cravens et al.* [1987]. The same chemical reaction schemes in *Ma et al.* [2004] and

²³⁷ *Najib et al.* [2011] are used, but with more realistic collision frequencies between species

²³⁸ [*Schunk and Nagy*, 2009]. At the model lower boundary, the densities of O^+, O_2^+, CO_2^+

²³⁹ satisfy the photochemical equilibrium condition (refer to Chapters 8 and 13 (e.g., Figure

²⁴⁰ 13.1) of *Schunk and Nagy* [2009] for detailed ionospheric chemistry), and the velocity **u** is

²⁴¹ set to satisfy a reflective boundary condition, which leads to approximately zero velocity

²⁴² at the inner boundary, as expected. At the inner boundary, both ions and electrons have

²⁴³ roughly the same temperature as the neutrals due to collisions. Therefore, it is a reason-

²⁴⁴ able assumption to set the plasma temperature to be twice the neutral temperature (i.e.,

²⁴⁵ $T_{plasma} = T_i + T_e = 2T_n$). The crustal fields are implemented by the 60 degree harmonic

²⁴⁶ expansion developed by *Arkani-Hamed* [2001], which can well describe the observed fields

²⁴⁷ at Mars [*Acuña et al.*, 1999] and is particularly good at the MGS altitude ($\sim$ 400 km).

²⁴⁸ A nonuniform, spherical grid structure is used in the model, where the radial resolution

249   varies from 5 km ($\sim$ 0.5 scale height, i.e., the vertical distance over which the density and

250   pressure fall by a factor of 1/e) at the lower boundary ($\sim$ 100 km) to 1000 km at the outer

251   boundary ($\sim$ 20 R_M). The angular resolution varies from 1.5° to 3.0°. The simulation

252   domain is defined by -24 $R_M \leq$ X $\leq$ 8 R_M; -16 $R_M \leq$ Y,Z $\leq$ 16 R_M.

253   Recently, *Dong et al.* [2014] successfully employed a one-way coupling between the

254   MF-MHD model and the 3-D M-TGCM model [*Bougher et al.*, 2000, 2006] along with

255   a 1-D spherically symmetric hot corona model [*Kim et al.*, 1998] to study the effects

256   of the 3-D cold neutral atmosphere on ion escape rates. However, *Dong et al.* [2014]

257   did not investigate the effects of varying inhomogeneous crustal field orientations and

258   seasons on the Martian upper atmosphere ion loss. Moreover, as we described above, the

259   M-TGCM model may not be able to handle the extreme cases (i.e., resulting in large

260   vertical velocities) due to the hydrostatic assumption. M-TGCM is an upper atmosphere

261   model which takes the NASA Ames Mars General Circulation Model outputs as its lower

262   boundary conditions [see *Bougher et al.*, 2008].

263   The MF-MHD model uses a nonuniform spherical grid in MSO coordinate system, M-

264   GITM uses a uniform spherical grid in GEO coordinate system, and M-AMPS adopts

265   a nonuniform Cartesian grid in GEO coordinate system. In order to one-way couple

266   the MF-MHD model with M-GITM and AMPS, we first need to carry out a coordinate

267   transformation and linear interpolation between different grids. For the hot atomic oxy-

268   gen, the AMPS output is able to cover the MF-MHD simulation domain from 100 km

269   to 5 R_M. For the M-GITM cold neutral profiles, we use the linear interpolation to cover

270   the MF-MHD domain from 100 km to 220 km. From 220 km to 5 R_M, we assume con-

271   stant neutral temperatures and photoionization frequencies, based on the M-GITM values

272 since these values are almost constant when approaching 220 km. For the neutral atmo-

273 sphere densities, however, we use an extrapolation based upon the hydrostatic assumption

274 which assumes the neutral atmosphere densities decrease exponentially with altitude, i.e.,

275 $n=n_0 \exp(-dz/H)$, where dz is the altitude change and H is the scale height (which depends

276 on the gravity, neutral temperature and neutral species mass). Technically speaking, the

277 hydrostatic assumption may not be accurate enough to describe the cold oxygen compo-

278 nent in the Martian exosphere, which should dominate the hot component up to 600 km

279 in altitude [*Feldman et al.*, 2011]. However, the comparison of model results (from the

280 one-way coupling between M-GITM and M-AMPS, Lee et al., 2015, submitted to JGR)

281 and ALICE/Rosetta observations of the OI 1304 $\mathring{A}$ brightness [*Feldman et al.*, 2011] shows

282 good agreement with each other on the transition altitude from cold to hot oxygen ($\sim$

283 600 km), indicating that our extrapolation approach is reasonable. It is noteworthy that

284 the cold oxygen component also plays an important role in the solar wind Mars interac-

285 tion, especially below 600 km. The cold and hot corona components should be able to

286 be calculated self-consistently in the future by adopting the two-way coupling approach

287 (Figure 1).

3. Simulation Results and Discussion

288   In this section, we discuss the simulation results by implementing the one-way coupling

289 approach mentioned in Section 2, i.e., both the M-GITM and AMPS 3-D outputs are

290 used as the inputs for the MF-MHD model (Figure 1). In order to evaluate the effects of

291 different crustal field orientations, plus various solar cycle and seasonal conditions on the

292 Mars upper atmosphere ion loss, we study 18 standard cases plus four cases without crustal

293 fields. The 18 cases combine three crustal field orientations (subsolar longitude, SSL=0°

₂₉₄ W, 180° W, 270° W), three Martian seasons (aphelion, autumnal equinox, perihelion) with

₂₉₅ solar maximum (F10.7=200) and solar minimum (F10.7=70) conditions. Due to the fact

₂₉₆ that there is no significant difference between vernal equinox and autumnal equinox (the

₂₉₇ heliospheric distance difference between these two cases is not zero but small), we only

₂₉₈ study the latter. For all the cases, the solar wind density is set to 4 cm^{-3}, the upstream

₂₉₉ solar wind plasma temperature is set to 3.5×10^5 K, the interplanetary magnetic field

₃₀₀ (IMF), B, is assumed to be a Parker spiral in the X-Y plane of MSO coordinate system

₃₀₁ with an angle of 56°, and the solar wind velocity is 400 km/s. Table 1 summarizes the

₃₀₂ cases studied in this paper.

₃₀₃   The calculated ion escape rates (in $\times 10^{24}$ s^{-1}) are summarized in Table 2 and the

₃₀₄ corresponding histograms are shown in Figure 4. The calculation of ion escape rate is

₃₀₅ conducted by integrals of the plasma density multiplied by the radial velocity component

₃₀₆ at the surface of a sphere far from the planet. Given the fact that the calculated ion

₃₀₇ escape rates do not change to any significant degree once the radius exceeds 4 R$_M$, we

₃₀₈ select the integral spherical surface to be 6 R$_M$. The results are quite interesting and

₃₀₉ several conclusions can be made.

3.1. Effects of crustal field orientation

₃₁₀   First, the crustal magnetic field has a shielding effect to protect Mars from the solar wind

₃₁₁ interaction and is therefore able to reduce the ion escape rates. For example, comparison

₃₁₂ of cases in the AEQUMIN conditions (cases 7-9) shows that case 8 (SSL=180°W, crustal

₃₁₃ field, B$_c$, mainly faces the Sun) has the smallest net ion escape rate (O$^+$, O$_2^+$ and CO$_2^+$)

₃₁₄ and case 7 (SSL=0°W, B$_c$ mainly faces the tail region) has the largest net ion escape rate

₃₁₅ among these three cases. Interestingly, the same conclusion is not valid for aphelion and

316   perihelion conditions due to the axial tilt, inhomogenous distribution of the crustal field,

317   and possibly the 3-D atmosphere profiles (e.g., the effect of surface albedo and thermal

318   inertia in M-GITM). For aphelion conditions, even when SSL=180 (cases 2 and 5), the

319   crustal magnetic field is mainly concentrated in the southern hemisphere polar region in

320   the MSO coordinate system (as indicated by Figure 2). Therefore, the crustal field does

321   not play a significant role in the solar wind Mars interaction like in the equinox cases.

322   For perihelion conditions, when SSL=180 (cases 14 and 17), the crustal magnetic field

323   is mainly concentrated in the dayside equatorial region (almost exactly facing the Sun).

324   The shielding effect of the crustal field under this circumstance is stronger than those in

325   the equinox cases.

326   Contrary to our initial expectation, the smallest net escape rate is associated with the

327   AEQUMIN conditions when the crustal magnetic field faces the Sun (case 8, 1.53×10^{24}

328   s^{-1}) instead of the APHMIN conditions with the same crustal field orientation (case 2,

329   2.12×10^{24} s^{-1}). This behavior indicates that considering only the heliocentric distance or

330   the associated chemical reaction rates is not sufficient to determine the ion escape rates

331   due to the influence of the crustal magnetic field. According to our simulation, case 18

332   (PERMAX, SSL=270) has the largest net ion escape rate, 9.43×10^{24} s^{-1}. Although the

333   existence of the axial tilt and the potential influence of the 3-D atmosphere can break

334   the simple conclusion we draw for the equinox conditions, overall the crustal field shows

335   a strong shielding effect to prevent the ion loss from the solar wind Mars interaction.

336   It is interesting to point out that both hybrid models [e.g., *Brecht and Ledvina*, 2014a]

337   and other MF-MHD codes [e.g., *Harnett and Winglee*, 2006] also showed that the crustal

338   field has a strong shielding effect to protect Mars from the solar wind interaction regard-

₃₃₉ less of different model setups and inputs. Meanwhile, *Riousset et al.* [2014] pointed out

₃₄₀ that the ionospheric outflows are likely to be prevented when the surface and lower at-

₃₄₁ mospheres are shielded by closed field lines due to the presence of magnetic loops and

₃₄₂ arcades. Such shielding ultimately reduces the fluxes of ions from the dynamo region to

₃₄₃ the upper ionosphere and thus reducing the ion escape rate. Furthermore, *Lundin et al.*

₃₄₄ [2011] studied how the ionospheric O^+ outflow and escape are related to the crustal mag-

₃₄₅ netic field regions by analyzing the ASPERA-3 data from MEX. They found that a large

₃₄₆ fraction of the energized O^+ ions remain magnetically trapped and are recycled within

₃₄₇ the mini-magnetospheres generated by the small-scale planetary crustal field regions at

₃₄₈ Mars. When the crustal field faces the sun, it has an effect to deviate the dayside ion flow

₃₄₉ and thus reducing the tailward transport and escape of ionospheric plasma.

3.2. Effects of seasonal variations

₃₅₀ Second, by averaging over different crustal field orientations and solar cycle conditions,

₃₅₁ we found that aphelion conditions (APH) are associated with a net ion escape rate of

₃₅₂ 4.03×10^{24} s^{-1}, autumnal equinox conditions (AEQU) are associated with a net ion escape

₃₅₃ rate of 4.40×10^{24} s^{-1}, and perihelion conditions (PER) yield an increased net ion escape

₃₅₄ rate up to 5.37×10^{24} s^{-1}. As expected, perihelion has the largest net ion escape rate and

₃₅₅ aphelion has the smallest total ion loss rate. According to the values mentioned above,

₃₅₆ the seasonal variations may cause a factor of ~ 1.33 variation in the ion loss rate.

₃₅₇ Although we try to eliminate the effect of crustal field when estimating the ion escape

₃₅₈ affected by seasonal variations alone, the crustal field still has a potential effect on the

₃₅₉ results due to the axial tilt. In other words, the seasonal variations and crustal mag-

₃₆₀ netic field orientations are closely connected with each other, and may not be simply

decoupled by averaging over different B_c orientations and solar cycles. With different

crustal field orientations but the same solar cycle and seasonal conditions, we calculated

the ratio of maximum net ion loss to minimum ion loss for APHMIN (2.18/1.86∼1.17),

APHMAX (6.33/5.44∼1.16), and the average of APHMIN and APHMAX, APH (∼1.17);

AEQUMIN (2.24/1.53∼1.46), AEQUMAX (7.40/5.86∼1.26) and AEQU (∼1.36); PER-

MIN (2.94/2.14∼1.37), PERMAX (9.43/6.80∼1.39) and PER (∼1.38). Based on the

results, we could easily prove that the shielding effect of crustal field are significantly

correlated with season. Figure 4 may help to illustate this conclusion in a more intuitive

way. The crustal field has a more significant shielding effect for perihelion conditions than

for the aphelion conditions due to the axial tilt.

In order to investigate the seasonal control of the ion loss more accurately, we calcu-

lated four more cases without the crustal magnetic field: APHMIN, APHMAX, PERMIN

and PERMAX, in which all SSL=180 °W. Surprisingly, we obtained a factor of ∼ 1.29

variation in the ion escape due to different seasons, which is only slightly smaller (within

5%) than the previous estimate ∼ 1.33, based on the average of results obtained with

three crustal field orientations. Therefore, it may be appropriate to estimate the seasonal

control of the ion loss by averaging over different crustal field orientations, but further

investigations with more crustal field orientations or a real-time case are needed to verify

this argument. Compared with the corresponding cases with crustal magnetic fields, all

the ion escape rates increase (also see Figure 4) when crustal field is turned off, consistent

with the first conclusion drawn above. On the other hand, the ion escape rate of case 18

is generally higher than that of case 22, indicating that the crustal field may also help ions

to escape from the Martian upper atmosphere under certain circumstances, e.g., magnetic

384   reconnection. The results may also be caused by the different M-GITM atmospheric pro-

385   files (with different subsolar longitudes) used in these two cases. Currently, surface albedo

386   and thermal inertia are the only two parameters implemented into M-GITM that can af-

387   fect atmospheric profiles during Mars' rotation [*Bougher et al.*, 2015]. In other words, if

388   one turns off these two parameters, all the atmospheric profiles are identical regardless of

389   the subsolar longitude. Although these two parameters may affect the upper atmosphere

390   profile to some extent, they are more important for the lower atmospheric structure via

391   the radiative transfer process. At present, M-GITM does not include surface topography.

3.3. Effects of solar cycle conditions

392   Third, by averaging over different crustal field orientations and seasonal variations,

393   we obtained that the net ion escape rate for solar maximum conditions (SOLARMAX,

394   7.06×10^{24} s^{-1}) is about 3.3 times higher than that of solar minimum conditions (SO-

395   LARMIN, 2.14×10^{24} s^{-1}). In other words, different solar cycles can affect the ion escape

396   rate by a factor of ~ 3.3 based on our simulations. Our calculated total ion escape rate

397   for SOLARMIN conditions is $\sim 2 \times 10^{24}$ s^{-1}, in reasonable agreement with the MEX data

398   as shown in Figure 4 in *Lundin et al.* [2013]. For SOLARMAX conditions, the calculated

399   result is 7.06×10^{24} s^{-1}, which is also reasonably consistent with the ion escape rate esti-

400   mate from MEX data, $\sim 1 \times 10^{25}$ s^{-1} [*Lundin et al.*, 2013]. The increasing trend of the ion

401   escape rate with solar activity is somewhat different from what reported by *Lundin et al.*

402   [2013] (a factor of ~ 10). One possible explanation is that we did not include the neutral

403   wind in our simulations, which can greatly affect the ion loss [*Brecht and Ledvina*, 2014b].

404   On the other hand, the recent paper published by *Ramstad et al.* [2015] showed that the

405   solar wind density and velocity can greatly affect the ratio of escape rate between low and

high solar EUV conditions. They adopted more than seven years of ion flux measurements in the energy range 10 eV–15 keV from ASPERA-3/IMA instrument on board MEX. As shown in their Figure 5, it is clear that based on our simulation parameters (solar wind velocity 400 km and solar wind density 4 cm^{-3}), the escape rate ratio is less than 10.

A careful analysis of individual mass spectra in *Lundin et al.* [2009] shows that the CO_2^+ contribution to the low-energy (< 300 eV) heavy ion outflow is $\leq 10\%$. On average, our CO_2^+ ion contribution to the total ion escape (O$^+$, O$_2^+$ and CO$_2^+$) is about 6.85% for SOLARMIN conditions and 5.30% for SOLARMAX conditions; both these values and the ratio from ALL conditions (as shown in Table 2, $\sim 5.66\%$) are consistent with the observations ($< 10\%$). *Nilsson et al.* [2011] pointed out that the average flux ratio of the molecular species (O$_2^+$ and CO$_2^+$) to O$^+$ ions is 0.9 ± 0.1 based on the statistics of MEX data from May 2007 to May 2011 for ion energies below 50 eV. Our escape rate ratio of molecular (O$_2^+$ and CO$_2^+$) to O$^+$ ions varies case by case as shown in Table 2. Since the estimate by *Nilsson et al.* [2011] is based upon a four-year average, the calculated ratio should be independent of seasonal variations given the fact that one Martian year is approximately equal to two Earth's years. Based on our calculations, this ratio is $\sim$ 4.16 for SOLARMIN conditions and 0.72 for SOLARMAX conditions. The average over solar cycles leads to a ratio of 1.04 (ALL conditions as shown in Table 2), in reasonable agreement with the MEX data. The MEX data used in previous studies [*Nilsson et al.,* 2011] was collected only from low solar activity to moderate level, but our result is based on the average over two solar cycle conditions. The other important factor that can lead to a difference is that their estimate of the flux ratio was based on ion energies below 50 eV, while our calculations include ions from all energy ranges. The low energy limit

429 in their calculation underestimates the high energy escape ions. It is noteworthy that

430 although M-GITM and M-AMPS provide the MF-MHD code with more realistic 3-D

431 cold and hot neutral atmosphere profiles (Figure 2 and Figure 3), currently there are few

432 accurate measurements of the (thermal and suprathermal) oxygen profiles in the Mars

433 atmosphere [*Bougher et al.*, 2014]. This uncertainty affects the calculated ion escape

434 rates. Therefore, the neutral atmosphere profiles to be returned by the MAVEN mission

435 will significantly reduce the uncertainty in calculated escape rates resulting from the lack

436 of direct information regarding the cold and hot oxygen abundances.

437   Figure 5 shows a comparison of H^+, O_2^+ and O^+ ion escape plumes in the $x - z$ plane of

438 the MSO coordinate system for two extreme cases: APHMIN (case 1) and PERMAX (case

439 18). The main feature of the MF-MHD model is the asymmetric escape plume for heavy

440 ion (O^+, O_2^+) species. The lack of significant escape plume for H^+ ions is because of its

441 small mass (and thus small gyroradius) and the fact that the solar wind and ionospheric

442 protons are combined in the model [*Najib et al.*, 2011]. The plume provides a channel

443 for ions to escape which cannot be reproduced by the multi-species MHD model [*Ma

444 et al.*, 2004; *Ma and Nagy*, 2007]. The asymmetry is primarily caused by different Lorentz

445 forces acting on each ion species [*Najib et al.*, 2011; *Dong et al.*, 2014]. From the particle

446 simulation point of view, the asymmetry can also be explained by the induced electric

447 field [*Fang et al.*, 2010; *Curry et al.*, 2013, 2014]. From Figure 5, it is not difficult to

448 distinguish the aphelion case from the perihelion case according to the different strengths

449 of the ion escape plume, primarily caused by different solar radiation. The upper panel is

450 associated with aphelion conditions which has a weaker ion escape plume than the bottom

451 panel for perihelion conditions, especially when focusing on the hot oxygen corona region

452 of the contour plot. The contour plots shown in Figure 5 are also consistent with the hot

453 oxygen profiles shown in Figure 3 and the ion escape rates shown in Table 2.

3.4. Effects of mass differentiation

454 Last but not least, all the ion escape rates show a positive linear correlation with

455 each other (Figure 6). The cold heavy ionospheric molecular ion escape fraction [(O_2^+

456 and/or CO_2^+)/Total] is inversely proportional to the atomic ion escape fraction [O^+/Total],

457 whereas O_2^+ and CO_2^+ ion escape fractions show a positive linear correlation (Figure 7).

458 The escape fraction is defined as the escape rate ratio between an individual or sum of

459 several ion species to total ions. The positive linear correlation in Figure 6 is mainly

460 caused by the fact that an increase in solar irradiance leads to a higher amount of ionized

461 gas via photoionization. Although the perfect linear anti-correlation in Figure 7 (d) is

462 mathematically to be expected, all the linear correlations indicated in Figure 7 can also

463 be physically interpreted. As we mentioned above, Mars has a solar cycle dependent

464 hot atomic oxygen corona (see Figure 3), which is ionized by the solar radiation and

465 the solar wind electrons via photoionization and electron impact ionization, respectively.

466 The ionized O^+ can be picked up by the solar wind and escape from the Martian upper

467 atmosphere. The mass loading process reduces the solar wind speed and the dynamic

468 pressure, and thus the solar wind has less chance to penetrate deep into the Martian

469 ionosphere mainly due to the momentum conservation. As a result, the cold heavy iono-

470 spheric molecular ions (O_2^+ and CO_2^+) are relatively less affected by the solar wind and

471 the associated ion escape rate fraction [(O_2^+ + CO_2^+)/Total] is decreased. Besides, the

472 ionized hot oxygen corona behaves approximately as a perfect conductor and therefore

473 prevents the electric and magnetic fields from penetrating into the Martian ionosphere

474 to a certain degree. Both the mass loading and electromagnetic shielding contribute to

475 the inverse correlation between the cold heavy ionospheric molecular ion escape fraction

476 [(O_2^+ and/or CO_2^+)/Total] and the atomic ion escape fraction [O^+/Total]. Meanwhile, O_2^+

477 and CO_2^+ ion escape fractions (ionospheric ion outflow) show a positive linear correlation

478 (r-value=0.68) because both species are originated from the cold Martian ionosphere and

479 should follow the same escape path. In order to avoid any artificial factor resulting from

480 both the small datasets and missing the solar moderate cases, we decided to adopt the

481 linear regression rather than a cubic polynomial regression fit to increase the correlation

482 coefficient (r-value). In the future work, we plan to add the datasets from the solar mod-

483 erate cases for the linear regression, most of which should lie in the middle of Figures 6

484 and 7, and thus may help increase the r-value.

485   In Figures 6 and 7, the calculated ion escape rates and the ion escape rate fractions (with

486 respect to the total ion loss) associated with solar minimum and solar maximum conditions

487 are indicated by the red circle and blue square markers, respectively. The corresponding

488 mean values are highlighted by the green markers with the same shape in both Figures.

489 The least squares polynomial linear fit of the simulation results based on cases 1-18 (2

490 average green points are not included) is shown in each figure as well. Correlations among

491 different ion escape rates and the corresponding correlations among their fractions for

492 different solar cycle conditions help us to understand the physics behind the regression

493 lines. For example, during the period of high solar activity, Mars has a more extensive hot

494 oxygen corona (see Figure 3), so the O^+ ion escape fraction is relatively large in Figure

495 7 (mainly distributed in the lower right corner when O^+/Total is the horizontal axis)

496 while the cold heavy ionospheric molecular ion escape fraction is relatively small. The

₄₉₇ associated statistical details, e.g., slope and intercept of the regression line, correlation

₄₉₈ coefficient (r-value), coefficient of determination (r-squared, R^2), two-sided p-value and

₄₉₉ standard error of the estimate (stderr) are shown in Table 3.

₅₀₀   The r-value is a measure of the linear correlation (dependence) between two variables

₅₀₁ X and Y, giving a value between +1 and -1, where 1 is total positive correlation, 0 is no

₅₀₂ correlation, and -1 is total negative correlation. It is defined as the (sample) covariance

₅₀₃ of the variables divided by the product of their (sample) standard deviations. The coef-

₅₀₄ ficient of determination, denoted R^2 or r^2, is a number that indicates how well data fits

₅₀₅ a statistical model. Two-sided p-value indicates the probability of the correlation occur-

₅₀₆ ring by random chance. Standard error of the estimate (stderr) represents the average

₅₀₇ distance that the observed values fall from the regression line. Conveniently, it tells you

₅₀₈ how wrong the regression model is on average using the units of the response variable.

₅₀₉ Smaller values are better because it indicates that the observations are closer to the fit

₅₁₀ line. The linear correlation in Figures 6 and 7 is very useful when one does not have all

₅₁₁ the ion escape information and/or the spacecraft instrument mass resolution is not high

₅₁₂ enough to distinguish, e.g., O^+ and O_2^+. Knowing the total ion and O^+ ion escape rates,

₅₁₃ the cold heavy ionospheric molecular ion escape rate can simply be calculated based on

₅₁₄ the linear fits shown in Figure 7 (d). If one needs to distinguish between O_2^+ and CO_2^+,

₅₁₅ the linear fit in the plot of CO_2^+ versus O_2^+ (Figure 6 (c)) can be used.

₅₁₆   In addition to the comparison with the available MEX data, we also list our predictions

₅₁₇ here for the data to be returned by the MAVEN mission. Once the MAVEN datasets

₅₁₈ become available, we will conduct a detailed comparison between the three model results

₅₁₉ and MAVEN observational data. Such comparisons are essential to provide new insights by

520 coupling the three codes and to identify possible missing physics for future incorporation

521 into the models. On the other hand, these 3-D simulations can provide global context

522 for individual measurements; i.e. for example, predictions of the time history and certain

523 physical problems of interest, based on the limited spacecraft data, are possible. It will

524 be instructive to run a real-time case in the near future with the variable solar wind

525 parameters (density and velocity) from the solar wind ion analyzer (SWIA) and the IMF

526 from the magnetometer (MAG) instruments. Finally, investigators need to be careful

527 when they calculate the controlling factors regulating the seasonal variations of the solar

528 wind interaction. The coexistence of effects due to both crustal field location and the

529 planetary axial tilt may influence the estimate to a certain degree.

4. Conclusions

530 In summary, we studied the solar wind interaction with the Martian upper atmosphere

531 by using one-way coupling of three comprehensive 3-D models, i.e., both the M-GITM

532 thermosphere-ionosphere outputs and the M-AMPS exosphere hot atomic oxygen are used

533 as inputs for the MF-MHD model. The effects of crustal field orientation, solar cycle and

534 seasonal variations on the Martian upper atmosphere ion escape are investigated in detail

535 by comparing 22 cases. Different solar cycles can affect the ion loss by a factor of ~ 3.3,

536 while different seasons can vary the ion loss by a factor of ~ 1.3. The coexistence of crustal

537 field and axial tilt lead to a quite intricate solar wind-Mars interaction. There is no simple

538 conclusion that a certain crustal magnetic field orientation can lead to the smallest ion

539 escape rate as found in previous studies (e.g. *Ma and Nagy* [2007]). Instead, in this study,

540 we found that the smallest ion escape rate also depends on the seasonal variations due

541 to the axial tilt and the 3-D atmospheric structure. Overall, it is clear that the crustal

magnetic field has a shielding effect to protect Mars from the solar wind interaction, and this effect is the strongest for perihelion conditions with the crustal field facing the Sun. Furthermore, the cold heavy ionospheric molecular ion escape fraction $[(O_2^+$ and/or $CO_2^+)$/Total] is inversely proportional to the atomic ion escape fraction $[O^+$/Total]. On the other hand, O_2^+ and CO_2^+ ion escape fractions (ionospheric ion outflow) show a positive linear correlation.

Contrary to our initial expectation, the smallest total ion escape rate is associated with the autumnal equinox solar minimum (AEQUMIN) case instead of the aphelion solar minimum (APHMIN) case, again due to the effect of coexisting crustal field and axial tilt plus the 3-D atmosphere. Based on averages over different solar cycles and various crustal field orientations, perihelion conditions yield the highest total ion escape rate and aphelion conditions yield the lowest total ion escape rate, which is well within our expectations. The calculated ion escape rates are in reasonable agreement with the recent observational data from MEX. For solar minimum conditions, the total ion (O^+, O_2^+ and CO_2^+) escape rate is around 2.0×10^{24} s^{-1} and for solar maximum conditions, the net ion loss is 7.06 $\times 10^{24}$ s^{-1}. By averaging our 18 MHD model cases, we obtained CO_2^+/Total ($\sim 5.66\%$) and $(CO_2^+ + O_2^+)/O^+$ (~ 1.04), which are reasonably consistent with the statistical results from 4-year observational data.

This work aims to build a model library for the MAVEN mission, which has the potential to provide improved predictions of ion escape rates for comparison to future data to be returned by the MAVEN mission (2014-2016) and thereby improve our understanding of present escape processes. Estimates of ion escape rates over Mars history must start from

properly validated models that can be extrapolated into the past. This work will enhance

the science return from the MAVEN mission.

References

Acuña, M. H. et al. (1999), Global Distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment, *Science*, *284*, 790–793.

Arkani-Hamed, J. (2001), A 50-degree spherical harmonic model of the magnetic field of Mars, *Journal of Geophysical Research*, *106*, 23,197–23,208.

Barabash, S., A. Fedorov, R. Lundin, and J. A. Sauvaud (2007), Martian atmospheric erosion rates., *Science*, *315*, 501–503.

Bird, G. A., (1994), Molecular Gas Dynamics and the Direct Simulation of Gas Flows, 2nd ed., Clarendon Press, Oxford.

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, *Journal of Geophysical Research*, *105*, 17669–17692.

Bougher, S. W., J. M. Bell, J. R. Murphy, M. A. Lopez-Valverde, and P. G. Withers (2006), Polar warming in the Mars thermosphere: Seasonal variations owing to changing insolation and dust distributions, *Geophysical Research Letters*, *33*, L02,203.

Bougher, S. W., P.-L. Blelly, M. R. Combi, J. L. Fox, I. Mueller-Wodarg, A. Ridley, and R. G. Roble (2008), Neutral Upper Atmosphere and Ionosphere Modeling, *Space Sci. Reviews*, *139*, 107-141.

Bougher, S. W., T. M. McDunn, K. A. Zoldak, and J. M. Forbes (2009), Solar Cycle Variability of Mars Dayside Exospheric Temperatures: Model Evaluation of Underlying Thermal Balances, *Geophysical Research Letters*, *36*, L05201.

Bougher, S. W., T. E. Cravens, J. Grebowsky, and J. Luhmann (2014), The Aeronomy of Mars: Characterization by MAVEN of the Upper Atmosphere Reservoir that Regulates Volatile Escape, *Space Science Reviews*, doi:10.1007/s11214-014-0053-7.

Bougher, S. W., D. J. Pawlowski, J. M. Bell, S. Nelli, T. McDunn, J. R. Murphy, M. Chizek, and A. Ridley (2015), Mars global ionosphere-thermosphere model (MGITM): Solar cycle, seasonal, and diurnal variations of the Mars upper atmosphere, *Journal of Geophysical Research*, doi:10.1002/2014JE004715.

Brain, D., et al. (2010), A comparison of global models for the solar wind interaction with Mars, *Icarus*, *206*, 139–151.

Brain, D., et al. (2012), Comparison of global models for the escape of martian atmospheric plasma, AGU Fall Meeting Abstracts, P13C-1969.

Brecht, S. H., and S. A. Ledvina (2014a), The role of the Martian crustal magnetic fields in controlling ionospheric loss, *Geophysical Research Letters*, *41*, 5340–5346.

Brecht, S. H., and S. A. Ledvina (2014b), Hybrid Particle Code Simulations of Mars: The Role of Assorted Processes in Ionospheric Escape, AGU Fall Meeting Abstracts, P54A-06.

Chamberlin, P. C., T. N. Woods, F. G. Eparvier (2008), Flare Irradiance Spectral Model (FISM): Flare component algorithms and results, *Space Weather*, *6*, S05001.

Cravens, T. E., J. U. Kozyra, A. F. Nagy, T. I. Gombosi, and M. Kurtz (1987), Electron impact ionization in the vicinity of comets, *Journal of Geophysical Research*, *92*, 7341–7353.

Curry, S. M., M. W. Liemohn, X.-H. Fang, Y.-J. Ma, J. Espley (2013), The influence of production mechanisms on pick-up ion loss at Mars, *Journal of Geophysical Research*, *118*, 554–569.

Curry, S. M., M. W. Liemohn, X.-H. Fang, Y.-J. Ma, J. Slavin, J. Espley, S. Bougher, and C. F. Dong (2014), Test particle comparison of heavy atomic and molecular ion distributions at Mars, *Journal of Geophysical Research*, *119*, 2328–2344.

Curry, S. M., J. G. Luhmann, Y. Ma, M. W. Liemohn, C. Dong, and T. Hara (2015), Comparative pick-up ion distributions at Mars and Venus: Consequences for atmospheric deposition and escape, Planet. Space Sci., doi:10.1016/j.pss.2015.03.026.

Deng, Y., A. D. Richmond, A. J. Ridley, and H.-L. Liu (2008), Assessment of the non-hydrostatic effect on the upper atmosphere using a general circulation model (GCM), *Geophysical Research Letters*, *35*, L01104.

Dong, C., S. W. Bougher, Y. Ma, G. Toth, A. F. Nagy, and D. Najib (2014), Solar wind interaction with Mars upper atmosphere: Results from the one-way coupling between the multifluid MHD model and the MTGCM model, *Geophysical Research Letters*, *41*, 2708–2715.

Fang, X., M. W. Liemohn, A. F. Nagy, J. G. Luhmann, and Y. J. Ma (2010), On the effect of the martian crustal magnetic field on atmospheric erosion, *Icarus*, *206*, 130–138.

Feldman, P. D., A. J. Steffl, J. Wm. Parker, M. F. A'Hearn, J.-L. Bertaux, S. A. Stern, H. A. Weaver, D. C. Slater, M. Versteeg, H. B. Throop, N. J. Cunningham, L. M. Feaga (2011), Rosetta-Alice observations of exospheric hydrogen and oxygen on Mars, *Icarus*, *214*, 394–399.

Glocer, A., G. Tóth, Y. J. Ma, T. I. Gombosi, J. C. Zhang, and L. M. Kistler (2009), Multifluid Block-Adaptive-Tree Solar Wind Roe-Type Upwind Scheme: Magnetospheric composition and dynamics during geomagnetic storms–Initial results, *J. Geophys. Res.*, *114*, A12203.

Haberle, R. M., M. M. Joshi, J. R. Murphy, J. R. Barnes, J. T. Schofield, G. Wilson, M. Lopez-Valverde, J. L. Hollingsworth, A. F. C. Bridger, and J. Schaeffer (1999), General circulation model simulations of the Mars Pathfinder atmospheric structure investigation/meteorology data, *Journal of Geophysical Research*, *104*, 8957–8974.

Harnett, E. M., and R. M. Winglee (2006), Three-dimensional multifluid simulations of ionospheric loss at Mars from nominal solar wind conditions to magnetic cloud events, *J. Geophys. Res.*, *111*, A09213.

Johnson, R. E., J. G. Luhmann (1998), Sputter contribution to the atmospheric corona on Mars, *J. Geophys. Res.*, *103*, 3649-3653.

Kim, J., A. F. Nagy, J. L. Fox, and T. E. Cravens (1998), Solar cycle variability of hot oxygen atoms at Mars, *J. Geophys. Res.*, *103*, 29,339.

Lee, Y., M. R. Combi, V. Tenishev and S. W. Bougher (2013), Hot Oxygen Corona in Mars' Upper Thermosphere and Exosphere: A Comparison of Results using the MGITM and MTGCM, AGU Fall Meeting Abstracts, P21A-1703.

Lee, Y., M. R. Combi, V. Tenishev and S. W. Bougher (2014a), Hot carbon corona in Mars' upper thermosphere and exosphere: 1. Mechanisms and structure of the hot corona for low solar activity at equinox, *Journal of Geophysical Research*, *119*, 905–924.

Lee, Y., M. R. Combi, V. Tenishev and S. W. Bougher (2014b), Hot Carbon Corona in Mars' Upper Thermosphere and Exosphere: 2. Solar Cycle and Seasonal Variability, *Journal of Geophysical Research*, doi:10.1002/2014JE004669.

Luhmann, J. G., W. T. Kasprzak, and C. T. Russell (2007), Space weather at Venus and its potential consequences for atmosphere evolution, *Journal of Geophysical Research*, *112*, E04S10.

Lundin, R., S. Barabash, M. Holmström, H. Nilsson, M. Yamauchi, M. Fraenz, and E. M. Dubinin (2008), A comet-like escape of ionospheric plasma from Mars, *Geophysical Research Letters*, *35*, L18,203.

Lundin, R., S. Barabash, M. Holmström, H. Nilsson, M. Yamauchi, E. M. Dubinin, and M. Fraenz (2009), Atmospheric origin of cold ion escape from Mars, *Geophysical Research Letters*, *36*, L17202.

Lundin, R., S. Barabash, M. Yamauchi, H. Nilsson, and D. Brain (2011), On the relation between plasma escape and the Martian crustal magnetic field, *Geophysical Research Letters*, *38*, L02102.

Lundin, R., S. Barabash, M. Holmström, H. Nilsson, Y. Futaana, R. Ramstad, M. Ya-
mauchi, E. M. Dubinin, and M. Fraenz, (2013), Solar cycle effects on the ion escape
from Mars, *Geophysical Research Letters*, *40*, 6028–6032.

Ma, Y. J., 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, *Journal of Geophysical Research*, *109*, A07,211.

Ma, Y. J., and A. F. Nagy (2007), Ion escape fluxes from Mars, *Geophysical Research
Letters*, *34*, L08,201.

Ma, Y. J., X. Fang, C. T. Russell, A. F. Nagy, G. Toth, J. G. Luhmann, D. A. Brain, and
C. Dong (2014), Effects of crustal field rotation on the solar wind plasma interaction
with Mars, *Geophysical Research Letters*, *41*, doi:10.1002/2014GL060785.

Modolo, R., G. M. Chanteur, and E. Dubinin (2012), Dynamic Martian magnetosphere:
Transient twist induced by a rotation of the IMF, *Geophys. Res. Lett.*, *39*, L01106.

Najib, D., A. F. Nagy, G. Tóth, and Y. J. Ma (2011), Three-dimensional, multifluid, high
spatial resolution MHD model studies of the solar wind interaction with Mars, *Journal
of Geophysical Research*, *116*, A05,204.

Nilsson, H., N. J. Edberg, G. Stenberg, S. Barabash, M. Holmström, Y. Futaana,
R. Lundin, and A. Fedorov (2011), Heavy ion escape from Mars, influence from so-
lar wind conditions and crustal magnetic fields, *Icarus*, *215*, 475–484.

de Pater, I., and J. J. Lissauer (2010), Planetary Sciences, 2nd ed., Cambridge Univ.
Press, New York, pp 5–6.

Powell, K. G., P. L. Roe, T. J. Linde, T. I. Gombosi, and D. L. De Zeeuw (1999), A
Solution-Adaptive Upwind Scheme for Ideal Magnetohydrodynamics, *J. Computational*

699   *Phys.*, *154*, 284–309.

700   Ramstad, R., S. Barabash, Y. Futaana, H. Nilsson, X.-D. Wang, M. Holmström (2015),

701   The Martian atmospheric ion escape rate dependence on solar wind and solar EUV

702   conditions I: Seven years of Mars Express observations, *Journal of Geophysical Research*,

703   doi:10.1002/2015JE004816.

704   Ridley, A., Y. Deng, and G. Toth (2006), The global ionosphere-thermosphere model, *J.*

705   *Atmos. Sol-Terr. Phys.*, *68*, 839.

706   Riousset, J. A., C. S. Paty, R. J. Lillis, M. O. Fillingim, S. L. England, P. G. With-

707   ers, and J. P. M. Hale (2013), Three-dimensional multifluid modeling of atmospheric

708   electrodynamics in Mars' dynamo region, *Journal of Geophysical Research*, *118*, 1–13.

709   Riousset, J. A., C. S. Paty, R. J. Lillis, M. O. Fillingim, S. L. England, P. G. Withers,

710   and J. P. M. Hale (2014), Electrodynamics of the Martian dynamo region near magnetic

711   cusps and loops, *Geophysical Research Letters*, *41*, 1119–1125.

712   Schunk, R. W., and A. F. Nagy (2009), Ionospheres, 2nd ed., Cambridge Univ. Press,

713   New York, pp102–109, chapter 8, pp 483.

714   Smith, M. D. (2004), Interannual variability in TES atmospheric observations of Mars

715   during 1999-2003, *Icarus*, *167*, 148–165.

716   Tenishev, V., and M. Combi (2008), A global kinetic model for cometary comae: The

717   evolution of the coma of the Rosetta target comet Churyumov-Gerasimenko throughout

718   the mission, *ApJ*, *685*, 659–677.

719   Tóth, G. et al. (2012), Adaptive Numerical Algorithms in Space Weather Modeling, *J.*

720   *Computational Phys.*, *231*, 870–903.

721 Valeille, A., V. Tenishev, S. W. Bougher, M. R. Combi, and A. F. Nagy (2009), Three-

722 dimensional study of Mars upper thermosphere/ionosphere and hot oxygen corona: 1.

723 General description and results at equinox for solar low conditions, *Journal of Geophys-*

724 *ical Research, 114*, E11005.

725 Verigin, M. et al. (1991), Ions of planetary origin in the Martian magnetosphere (Phobos

726 2/TAUS experiment), *Planetary and Space Science, 39*, 131–137.

Figure 1. A sketch of a one-way coupling approach between M-GITM, M-AMPS and the MF-MHD model. The notation T_n denotes neutral atmosphere temperatures, [O], [CO_2], [O_{hot}] are the neutral O, CO_2 and hot atomic oxygen number densities. Three photoionization processes are included. Here we focus on the one-way coupling indicated by the solid line. For the detailed study of one-way coupling between M-GITM and M-AMPS (dashed line), please refer to *Lee et al.* [2013, 2014a, b].

Figure 2. The neutral CO_2 and O number densities shown on a sphere at an altitude of 220 km above the Martian surface from M-GITM for perihelion solar maximum (PERMAX) and aphelion solar minimum (APHMIN) conditions. Two coordinate systems are indicated in each plot: the Geographic (GEO) and the Mars-centered Solar Orbital (MSO) coordinate systems. The spherical contour plots are shown in the $x - z$ plane (not a $x - z$ cut) of both coordinates. The subsolar point is highlighted in each plot.

Figure 3.   A comparison of the M-AMPS output hot oxygen number density (in

cm^{-3}) distribution between autumnal equinox solar minimum (AEQUMIN, case 7) and

maximum (AEQUMAX, case 10) conditions (upper panel), and aphelion solar minimum

(APHMIN, case 1) and perihelion solar maximum (PERMAX, case 16) conditions (bottom

panel) in the $x - z$ plane in the MSO coordinate system. All the results are based on the

subsolar longitude, SSL = 0. Note the use of a logarithmic scale.

Table 1.   Input parameters used for different calculations.

Simulation Cases	Subsolar Longitude (SSL)	Solar Cycle Conditions	Seasonal Variations
Case 1	0°W	Solar Minimum	
Case 2	180°W	(APHMIN)	
Case 3	270°W		Aphelion
Case 4	0°W	Solar Maximum	(APH)
Case 5	180°W	(APHMAX)	
Case 6	270°W		
Case 7	0°W	Solar Minimum	
Case 8	180°W	(AEQUMIN)	
Case 9	270°W		Autumnal Equinox
Case 10	0°W	Solar Maximum	(AEQU)
Case 11	180°W	(AEQUMAX)	
Case 12	270°W		
Case 13	0°W	Solar Minimum	
Case 14	180°W	(PERMIN)	
Case 15	270°W		Perihelion
Case 16	0°W	Solar Maximum	(PER)
Case 17	180°W	(PERMAX)	
Case 18	270°W		
Case 19	180°W	APHMIN	Aphelion and Perihelion
Case 20	180°W	APHMAX	comparison with
Case 21	180°W	PERMIN	crustal magnetic field
Case 22	180°W	PERMAX	turned off

Table 2. Calculated ion escape rates (in $\times 10^{24}$ s^{-1}).

Simulation Cases	O$^+$	O$_2^+$	CO$_2^+$	Total	(O$_2^+$ + CO$_2^+$)/O$^+$	CO$_2^+$/Total (%)
Case 1 (APHMINSSL0)	0.30	1.43	0.13	1.86	5.27	6.87
Case 2 (APHMINSSL180)	0.27	1.65	0.20	2.12	6.75	9.30
Case 3 (APHMINSSL270)	0.32	1.70	0.17	2.18	5.90	7.67
1-3 average (APHMIN)	0.30	1.59	0.16	2.05	5.95	7.99
Case 4 (APHMAXSSL0)	3.08	2.84	0.38	6.29	1.04	5.98
Case 5 (APHMAXSSL180)	2.64	2.38	0.41	5.44	1.06	7.63
Case 6 (APHMAXSSL270)	3.17	2.72	0.44	6.33	1.00	6.92
4-6 average (APHMAX)	2.96	2.64	0.41	6.02	1.03	6.81
1-6 average (APH)	1.63	2.12	0.29	4.03	1.48	7.11
Case 7 (AEQUMINSSL0)	0.41	1.68	0.15	2.24	4.42	6.90
Case 8 (AEQUMINSSL180)	0.31	1.12	0.11	1.53	4.01	6.89
Case 9 (AEQUMINSSL270)	0.44	1.45	0.13	2.02	3.60	6.46
7-9 average (AEQUMIN)	0.39	1.42	0.13	1.93	4.00	6.74
Case 10 (AEQUMAXSSL0)	4.57	2.52	0.26	7.35	0.61	3.49
Case 11 (AEQUMAXSSL180)	3.81	1.80	0.24	5.86	0.54	4.16
Case 12 (AEQUMAXSSL270)	4.99	2.17	0.24	7.40	0.48	3.25
10-12 average (AEQUMAX)	4.46	2.17	0.25	6.87	0.54	3.59
7-12 average (AEQU)	2.42	1.79	0.19	4.40	0.82	4.29
Case 13 (PERMINSSL0)	0.49	1.63	0.13	2.25	3.55	5.67
Case 14 (PERMINSSL180)	0.49	1.51	0.14	2.14	3.34	6.57
Case 15 (PERMINSSL270)	0.71	2.06	0.17	2.94	3.16	5.79
13-15 average (PERMIN)	0.56	1.73	0.15	2.44	3.33	5.98
Case 16 (PERMAXSSL0)	5.07	3.08	0.48	8.63	0.70	5.56
Case 17 (PERMAXSSL180)	4.02	2.40	0.38	6.80	0.69	5.62
Case 18 (PERMAXSSL270)	5.51	3.39	0.53	9.43	0.71	5.64
16-18 average (PERMAX)	4.86	2.96	0.46	8.29	0.70	5.61
13-18 average (PER)	2.71	2.35	0.31	5.37	0.98	5.69
1-3 & 7-9 & 13-15 average (SOLARMIN)	0.42	1.58	0.15	2.14	4.16	6.85
4-6 & 10-12 & 16-18 average (SOLARMAX)	4.10	2.59	0.37	7.06	0.72	5.30
1-18 average (ALL)	2.26	2.08	0.26	4.60	1.04	5.66
Case 19 (APHMINSSL180 [no B$_c$])	0.46	2.13	0.20	2.79	5.09	7.27
Case 20 (APHMAXSSL180 [no B$_c$])	3.13	2.69	0.43	6.26	1.00	6.94
19-20 average (APH [no B$_c$])	1.79	2.41	0.32	4.52	1.52	7.04
Case 21 (PERMINSSL180 [no B$_c$])	0.71	2.24	0.23	3.19	3.47	7.29
Case 22 (PERMAXSSL180 [no B$_c$])	5.41	2.51	0.56	8.48	0.57	6.58
21-22 average (PER [no B$_c$])	3.06	2.38	0.40	5.84	0.90	6.78

Figure 4. The histograms of ion escape rates (in s^{-1}). Upper panel: cases with solar minimum conditions; middle panel: cases with solar maximum conditions; bottom panel: average cases. Noted that the ion escape rate scales in these three plots are different.

Figure 5. The calculated ion number densities in cm^{-3} in the $x - z$ plane for H$^+$, O$_2^+$, and O$^+$ in a logarithmic scale. Case 1 is shown in the upper panels and case 18 is shown in the bottom panels. Noted that the logarithmic scales in different plots are different. The direction of the solar wind is parallel to the x-axis and in the $-x$ direction.

Figure 6. Least squares polynomial linear fit of the simulation results based on cases 1-18. The calculated ion escape rates associated with solar minimum and solar maximum conditions are indicated by the red circle and blue square markers, respectively. The corresponding mean values are highlighted by the green markers with the same shape.

Figure 7. Least squares polynomial linear fit of the simulation results based on cases 1-18. The calculated ion escape rate fractions (with respect to the net ion loss) associated with solar minimum and solar maximum conditions are indicated by the red circle and blue square markers, respectively. The corresponding mean values are highlighted by the green markers with the same shape. Although the perfect linear anti-correlation in Figure 7 (d) is mathematically to be expected, all the linear correlations indicated in Figure 7 can also be physically interpreted.

Table 3.   Slope and intercept of the regression line shown in Figure 7, correlation coefficient (r-value), coefficient of determination (r-squared, R^2), two-sided p-value for a hypothesis test whose null hypothesis is that the slope is zero, standard error of the estimate (stderr).

	slope	intercept	r-value	R^2	p-value	stderr
O_2^+ *vs.* O^+	0.264	1.49×10^{24}	0.833	0.694	1.776×10^{-5}	0.0438
CO_2^+ *vs.* O^+	0.0553	1.357×10^{23}	0.803	0.645	5.949×10^{-5}	0.0103
CO_2^+ *vs.* O_2^+	0.204	-1.647×10^{23}	0.937	0.878	9.95×10^{-9}	0.019
$O_2^+ + CO_2^+$ *vs.* O^+	0.319	1.626×10^{24}	0.835	0.698	1.592×10^{-5}	0.0525
O_2^+ *vs.* O^+ (fraction)	-0.948	0.919	-0.999	0.997	7.791×10^{-22}	0.0126
CO_2^+ *vs.* O^+ (fraction)	-0.052	0.081	-0.718	0.515	8.015×10^{-4}	0.0126
CO_2^+ *vs.* O_2^+ (fraction)	0.052	0.033	0.680	0.462	1.922×10^{-3}	0.014
$O_2^+ + CO_2^+$ *vs.* O^+ (fraction)	-1.0	1.0	-1.0	1.0	5.027×10^{-159}	0.0

M-AMPS

MF-MHD

M-GITM

$[O_{hot}]$
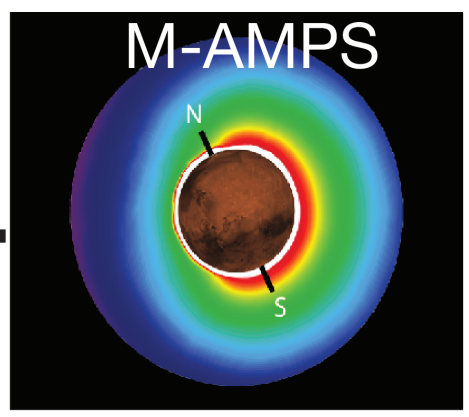
$[O],[CO_2],[CO],$
$[N_2],[O_2^+],$
$[e^-],T_e,T_i,T_n,$
U_n,V_n,W_n

$[O],[CO_2],T_n,$
Ionization frequencies
$(CO_2 \rightarrow CO_2^+, O \rightarrow O^+, CO_2 \rightarrow O^+)$
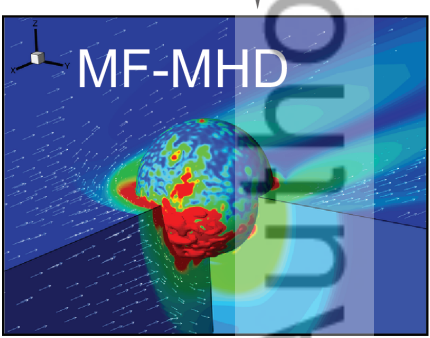
coupling
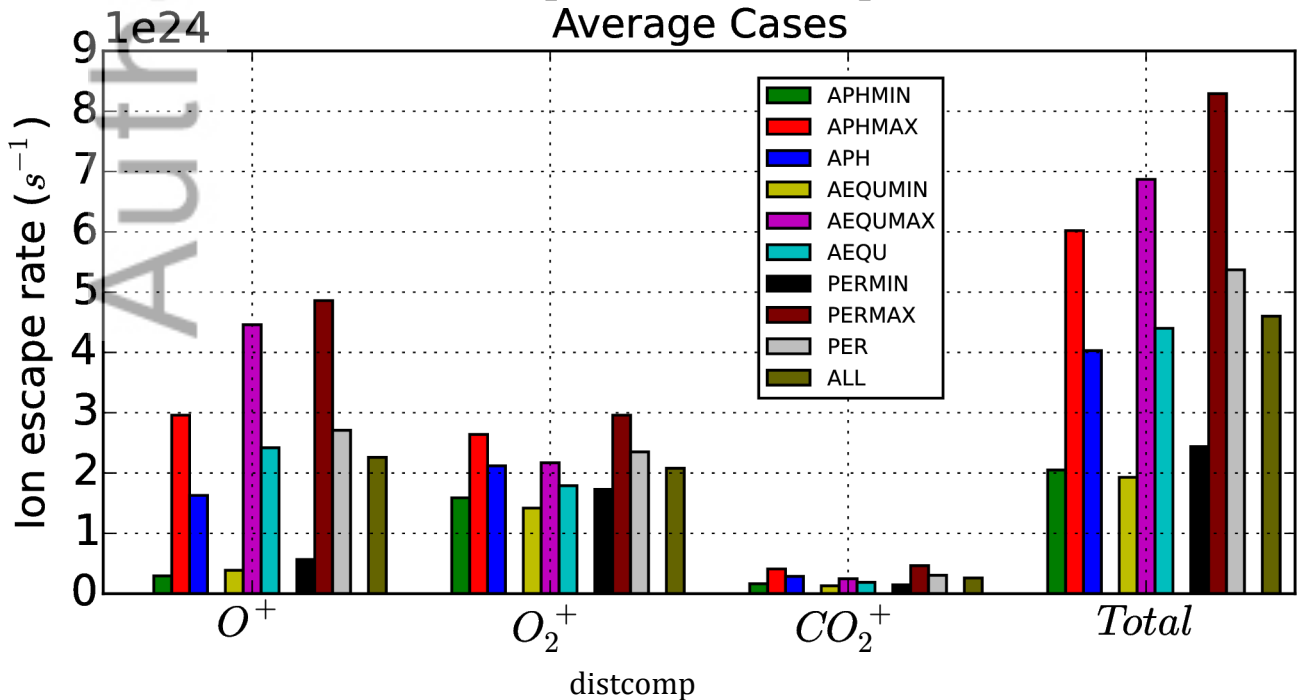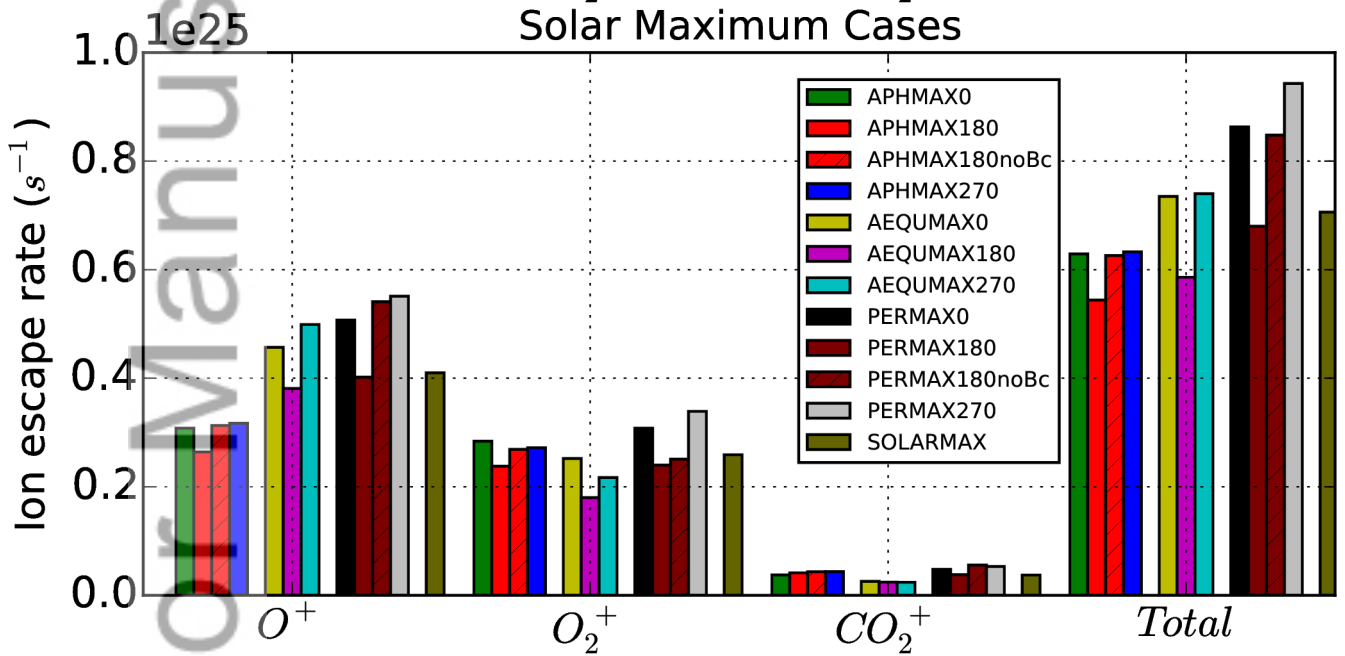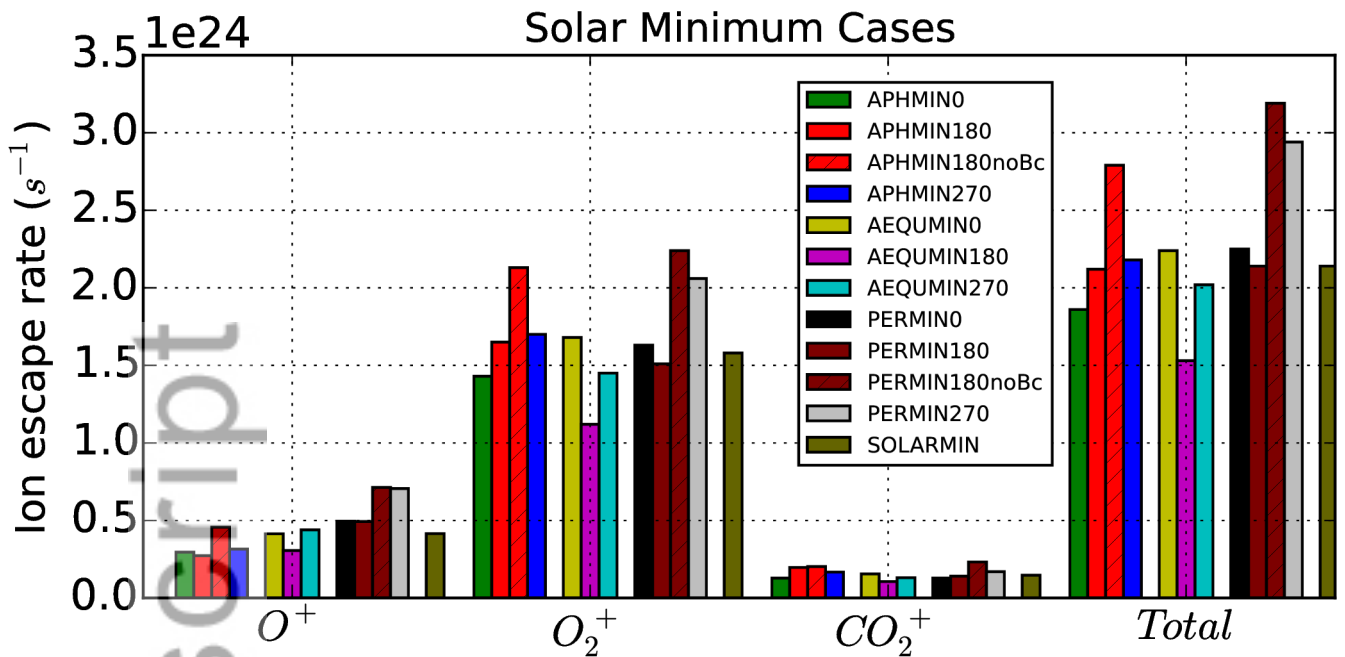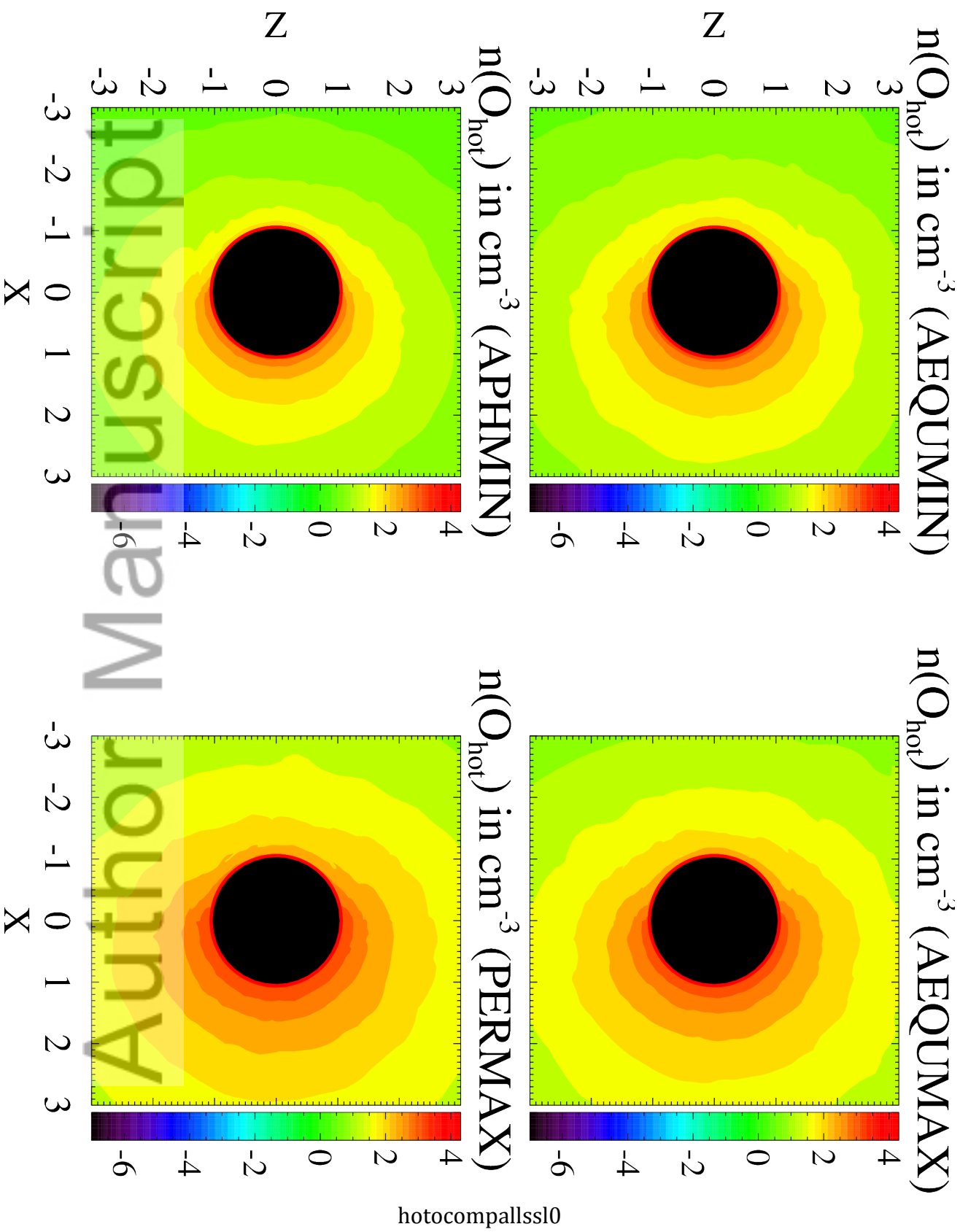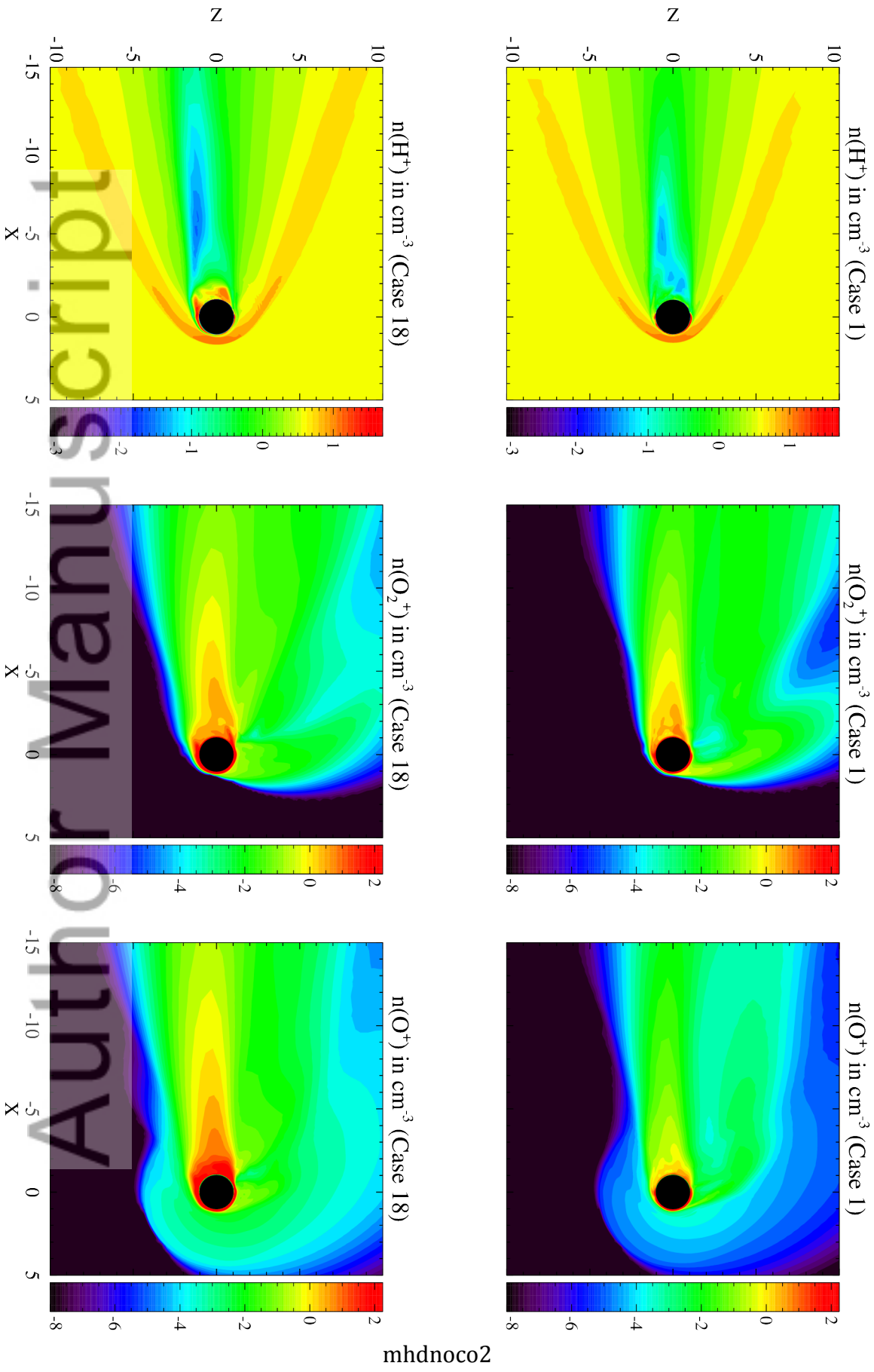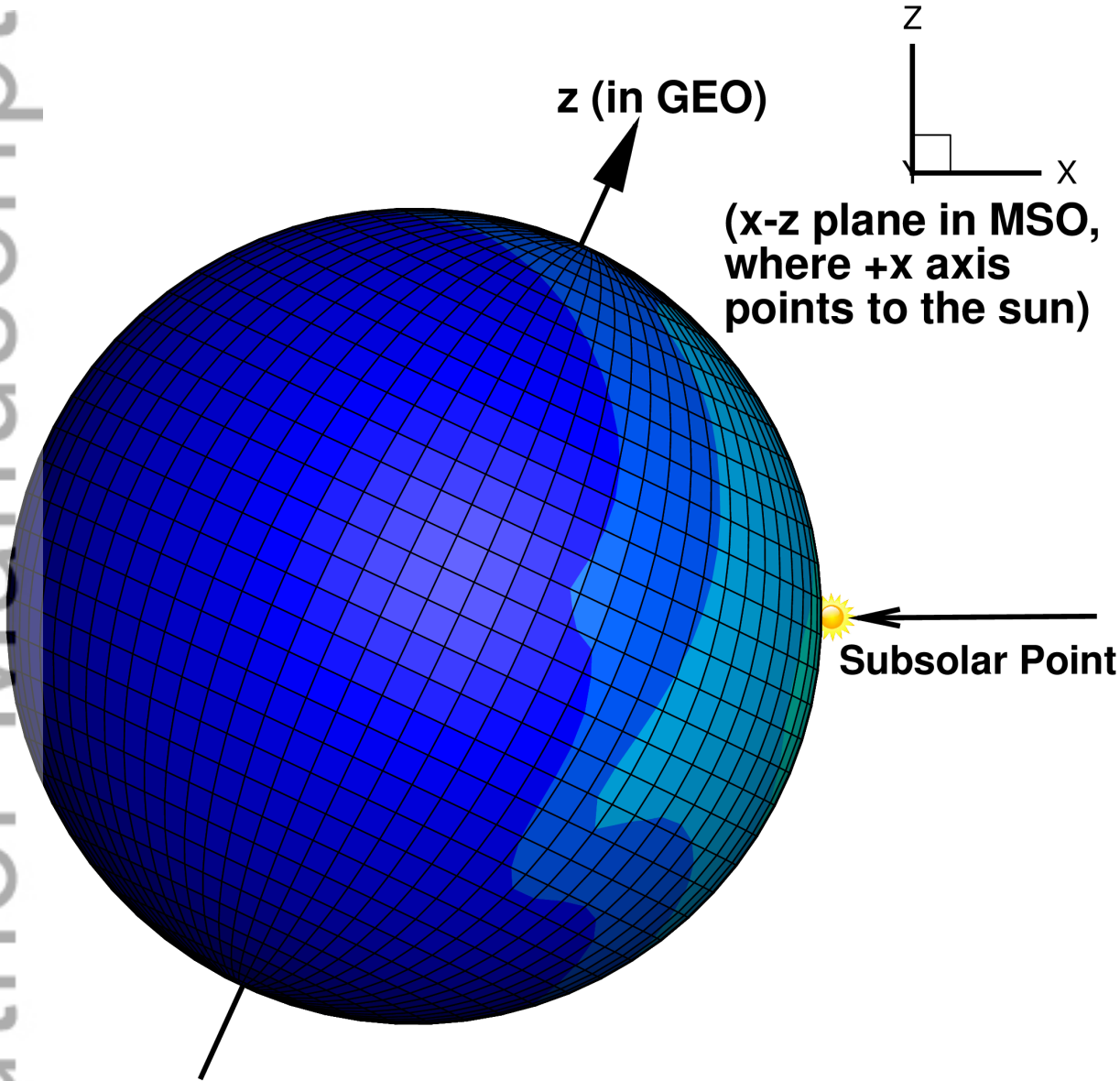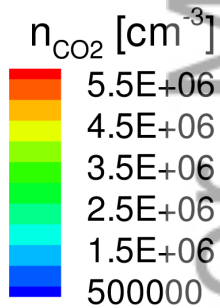
n(O_{hot}) in cm^{-3} (AEQUMIN)

n(O_{hot}) in cm^{-3} (AEQUMAX)

n(O_{hot}) in cm^{-3} (APHMIN)

n(O_{hot}) in cm^{-3} (PERMAX)

hotocompallssl0

n(H⁺) in cm⁻³ (Case 1)

n(H⁺) in cm⁻³ (Case 18)

n(O₂⁺) in cm⁻³ (Case 1)

n(O₂⁺) in cm⁻³ (Case 18)

n(O⁺) in cm⁻³ (Case 1)

n(O⁺) in cm⁻³ (Case 18)

mhdnoco2

CO$_2$

(APHMIN)

z (in GEO)

Z

X

(x-z plane in MSO, where +x axis points to the sun)

Subsolar Point

n_{CO2} [cm^{-3}]
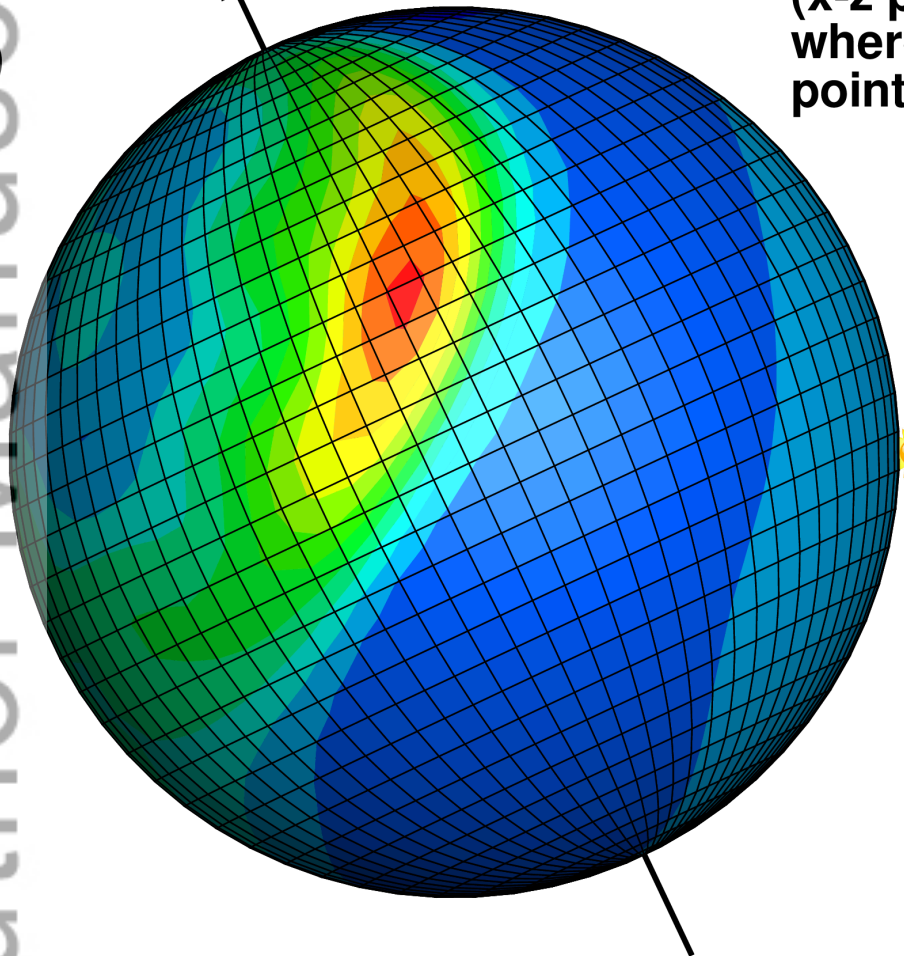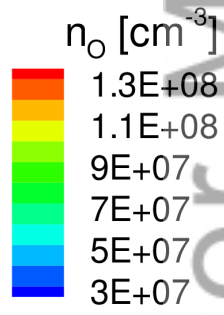
5.5E+06
4.5E+06
3.5E+06
2.5E+06
1.5E+06
500000

nco2aphmin

CO$_2$

(PERMAX)

z (in GEO)

Z

X

(x-z plane in MSO, where +x axis points to the sun)

n_{CO2} [cm^{-3}]

	1.5E+08
	1.3E+08
	1.1E+08
	9E+07
	7E+07
	5E+07
	3E+07
	1E+07
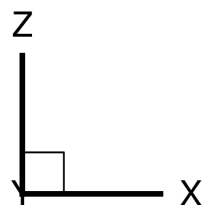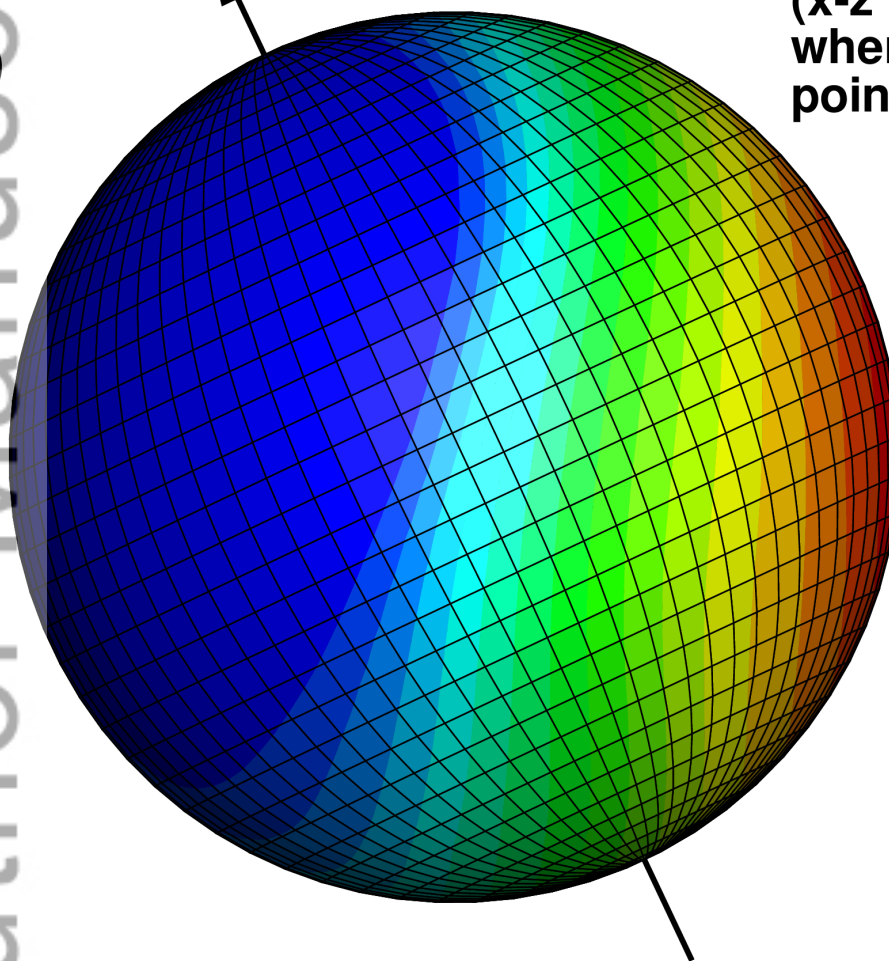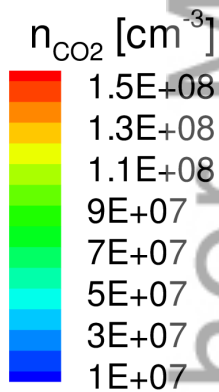
Subsolar Point

nco2permax
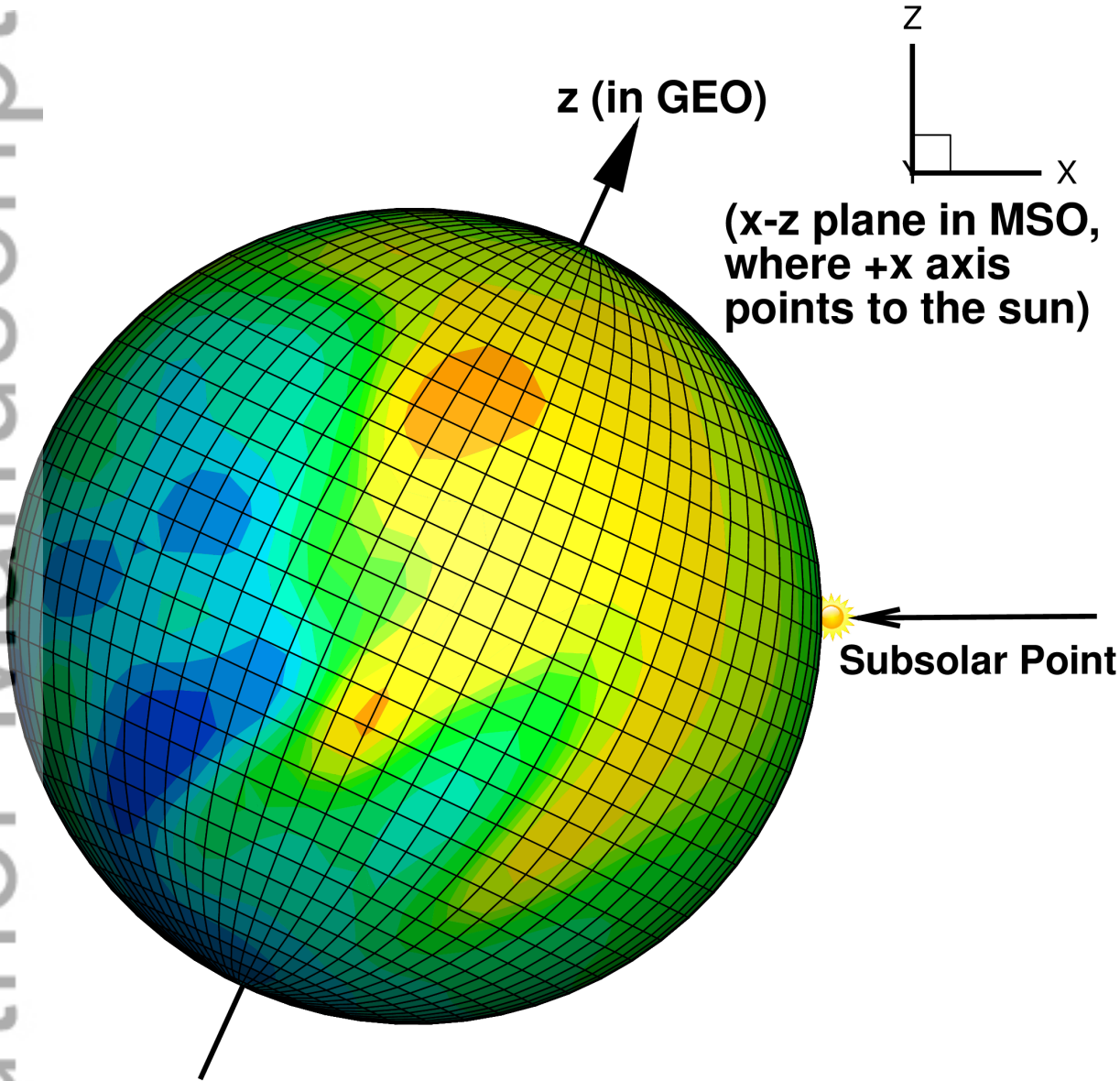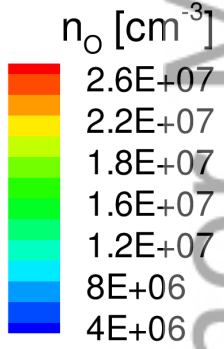
O
(APHMIN)

z (in GEO)

Z

X

(x-z plane in MSO, where +x axis points to the sun)

Subsolar Point

n_O [cm^{-3}]

2.6E+07
2.2E+07
1.8E+07
1.6E+07
1.2E+07
8E+06
4E+06

noaphmin

O
(PERMAX)

z (in GEO)

Z

X

(x-z plane in MSO,
where +x axis
points to the sun)

n_O [cm^{-3}]

1.3E+08
1.1E+08
9E+07
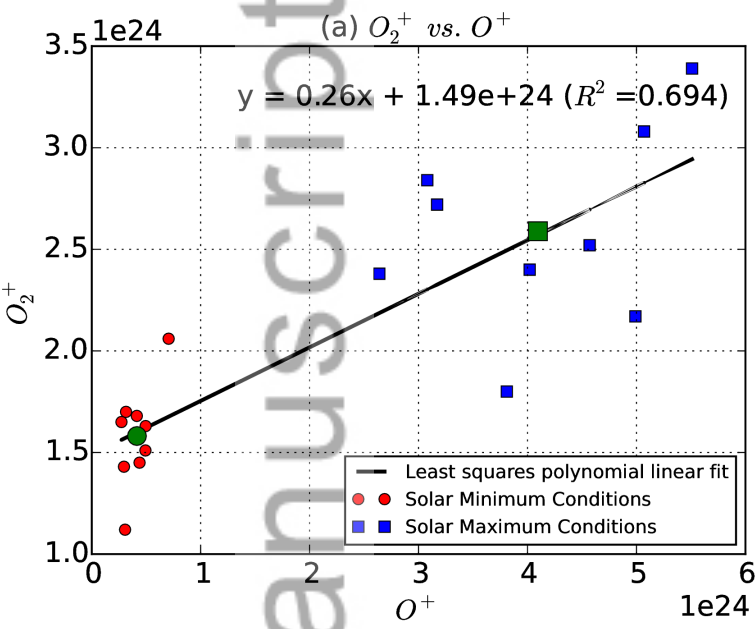7E+07
5E+07
3E+07
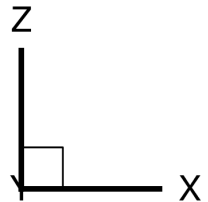
Subsolar Point

nopermax

(a) O_2^+ vs. O^+

$y = 0.26x + 1.49e{+}24$ $(R^2 = 0.694)$

(b) CO_2^+ vs. O^+

$y = 0.06x + 1.36e{+}23$ $(R^2 = 0.645)$

(c) CO_2^+ vs. O_2^+

$y = 0.2x - 1.65e{+}23$ $(R^2 = 0.878)$

(d) $O_2^+ + CO_2^+$ vs. O^+

$y = 0.32x + 1.63e{+}24$ $(R^2 = 0.698)$

— Least squares polynomial linear fit
● Solar Minimum Conditions
■ Solar Maximum Conditions

scatter

(a) O_2^+ vs. O^+

$y = -0.95x + 0.92 (R^2 = 0.997)$

- Least squares polynomial linear fit
- Solar Minimum Conditions
- Solar Maximum Conditions

(b) CO_2^+ vs. O^+

$y = -0.05x + 0.08 (R^2 = 0.515)$

- Least squares polynomial linear fit
- Solar Minimum Conditions
- Solar Maximum Conditions

(c) CO_2^+ vs. O_2^+

$y = 0.05x + 0.03 (R^2 = 0.462)$

- Least squares polynomial linear fit
- Solar Minimum Conditions
- Solar Maximum Conditions

(d) $O_2^+ + CO_2^+$ vs. O^+

$y = -1.0x + 1.0 (R^2 = 1.0)$

- Least squares polynomial linear fit
- Solar Minimum Conditions
- Solar Maximum Conditions

scatter_fraction