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# **Influence of the solar wind dynamic pressure on the ion precipitation: MAVEN observations and simulation results.**

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17 **Abstract:**

18 Using the data from the SWIA and STATIC instruments on board Mars Atmosphere and Volatile  
19 Evolution (MAVEN) and LatHyS (Latmos Hybrid Simulation) simulations, we investigate the heavy ion  
20 precipitation into the Martian atmosphere. We discuss the influence of the solar wind dynamic  
21 pressure on the ion precipitation using observations performed by MAVEN from 04 June 2014 to 20  
22 July 2017. The increase of the dynamic pressure from 0.63 to 1.44nPa is clearly associated with an  
23 increase of the same order of magnitude of the precipitating oxygen ion energy flux measured by  
24 MAVEN/STATIC from  $9.9$  to  $20.6 \times 10^6 \text{eV} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$  at low energy (from 30 to 650 eV). In the  
25 same way, from 650 eV to 25000 eV, MAVEN/SWIA (all species) observed an increase from 22.4 to  
26  $42.8 \times 10^7 \text{eV} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$  of the precipitating ion energy flux.

27 Performing two simulations using the average solar wind conditions for both solar dynamic pressure  
28 regimes observed by MAVEN as input in the LatHyS model, we reproduce some of the key  
29 characteristics of the observed oxygen ion precipitation. We characterize the oxygen ions simulated  
30 by LatHyS by their energy and time of impact, their time of injection in the simulation and initial  
31 position and the mechanism by which these ions were created. The model suggests that the main  
32 cause of the increase of the heavy ion precipitation during an increase of the solar dynamic pressure  
33 is the increase of the ion production by charge exchange, proportional to the increase of the solar wind  
34 flux, which becomes the main contribution to the ion precipitation at high energy.

35

36

## 37 I. Introduction

38

39 In the absence of a global magnetic field, Mars' upper atmosphere interacts directly with the solar  
40 wind. Planetary neutral species (mainly carbon dioxide molecules, hydrogen and oxygen atoms) are  
41 ionized by photoionization, electronic impact or charge exchange and are accelerated by the motional  
42 electric field of the solar wind. These charged particles can precipitate into Mars' atmosphere with  
43 energy up to several keV and induce a cascade of collisions, transferring enough energy to atmospheric  
44 particles to exceed the Martian escape velocity (Luhmann and Kozyra, 1991; Johnson, 1994). While  
45 this process, named atmospheric sputtering, may have led to significant atmospheric escape in its early  
46 history, as suggested by Luhmann et al. (1992), its contribution is nowadays minor compared to other  
47 neutral escape processes like Jeans escape (Anderson and Hord, 1971; Krasnopolsky and Feldman,  
48 2001) and photochemical escape (Lillis et al., 2015; 2017), or ion escape process like pick-up ions  
49 (Luhmann, 1990; Fang et al., 2010; Dong et al., 2017) and ion outflow (Lundin et al., 1990; Andersson  
50 et al., 2010).

51 Atmospheric escape induced by sputtering at the present epoch is expected to be small compared to  
52 other mechanisms (Leblanc et al. 2017) and therefore difficult to quantify from direct measurements.  
53 However, since heavy planetary ion precipitation (which we define as having mass larger or equal to  
54 the mass of carbon atom) is the primary driver of atmospheric sputtering (Johnson et al, 2000; Wang  
55 et al, 2014; 2015), it is essential to constrain the dependence of the precipitating ion flux on present  
56 solar wind conditions in order to, potentially, extrapolate the effect of this mechanism, over the  
57 Martian history. In situ measurements of precipitating ions began with Mars Express (MEX) spacecraft,  
58 in orbit around Mars since December 2003, (e.g., Chicarro et al., 2004; Barabash et al., 2006). Hara et  
59 al. (2011) reported that MEX observed enhancements of precipitating heavy ions (e.g.  $O^+$  and  $O_2^+$ )  
60 during the passage of Corotating Interaction Region (CIR) solar wind structures. This observation  
61 suggests that heavy ion precipitation is highly variable and depends on the upstream solar wind

62 conditions at Mars. Thanks to Mars Atmosphere and Volatile Evolution (MAVEN) measurements,  
63 observations of heavy ion precipitation during quiet solar wind conditions have been reported by  
64 Leblanc et al. (2015), suggesting that atmospheric sputtering occurs almost continuously at Mars.

65 Several investigations, either from observational or modeling studies, have highlighted the influence  
66 of the plasma properties on the Martian environment. Edberg et al. (2009), Hall et al. (2016), Halekas  
67 et al. (2017) and Ramstad et al. (2017) have shown that the solar EUV irradiance and the solar wind  
68 dynamic pressure have an influence on the position of plasma boundaries such as the Magnetic Pile-  
69 up Boundary (MPB) and the Bow Shock (BS). Indeed, the newly created exospheric ions can act to slow  
70 the solar wind flux, which can move the bow shock position away from the planet (Hall et al, 2016).  
71 Moreover, Lundin et al. (2008) also showed that the size of the Martian obstacle (estimated as  
72 proportional to the BS position) influences the ion atmospheric escape rate.

73 The statistical study by Hara et al. (2017a) has showed that precipitating ion fluxes observed by MAVEN  
74 (Jakosky et al., 2015) vary at least by an order of magnitude (typically between  $10^4 \text{ cm}^{-2} \cdot \text{s}^{-1} \text{sr}^{-1}$  and  
75  $10^6 \text{ cm}^{-2} \cdot \text{s}^{-1} \text{sr}^{-1}$  for ions with energies higher than 25 eV) depending on the upstream solar wind  
76 conditions such as the dynamic pressure, the magnitude of the interplanetary magnetic field, and the  
77 motional electric field direction  $\vec{E} = -\vec{V}_{\text{SW}} \times \vec{B}_{\text{SW}}$  with  $\vec{V}_{\text{SW}}$  the solar wind velocity and  $\vec{B}_{\text{SW}}$  the  
78 interplanetary magnetic field vector. Indeed, it has been shown by several theoretical studies  
79 (Luhmann and Kozyra 1991; Chaufray et al. 2007; Curry et al. 2015) that the orientation of the motional  
80 electric field may influence the energy and intensity of ion precipitation on Mars. These studies  
81 suggested that the integrated total precipitating ion fluxes are globally larger in the  $-\vec{E}$  hemisphere  
82 than in the  $+\vec{E}$  hemisphere. Pickup oxygen ions formed in the  $-\vec{E}$  hemisphere are accelerated towards  
83 Mars and can precipitate while oxygen ions formed in the  $+\vec{E}$  hemisphere are accelerated away from  
84 Mars and can escape. Such results have been observed by Martinez et al. (2019a) and Hara et al.  
85 (2017a) thanks to MAVEN.

86 Curry et al. (2015) have studied the response of Mars O<sup>+</sup> pickup ions to an ICME (March 8<sup>th</sup>, 2015) with  
87 a test-particle approach and found that the oxygen ion precipitation depends on the phase of the ICME  
88 with a maximum of precipitation during the shock. After the passage of the ICME shock, the  
89 precipitating flux of the ejecta phase decreases but still remains greater than the precipitating flux  
90 during the pre-ICME phase. Based on a similar approach, Fang et al. (2013) have shown that oxygen  
91 ion precipitation can vary by at least one order of magnitude due to the variation in dynamic pressure  
92 during ICME or CIR solar wind events. Similar conclusions have been reported by Hara et al. (2011)  
93 with Mars Express observation or by Martinez et al. (2019a) with MAVEN observations during the  
94 September 2017 solar events (Lee et al. 2018).

95 Complementary to observations, models can provide an extended set of information to better  
96 characterize the physical processes under investigations. By being able to take into account a wide  
97 variety of physical processes in time and space, models can be used to reproduce observations and  
98 investigate the resulting mechanisms. They provide a three-dimensional context for the observations.  
99 At the beginning of Martian exploration, with Mariner 4 or Phobos 2, computer simulations have been  
100 found very useful for investigating the physic mechanisms of the atmospheric escape (Luhmann and  
101 Kozyra, 1991; Luhmann, Jonhson & Zhang, 1992; Johnson, 1994; Leblanc & Johnson, 2001; 2002;  
102 Dubinin & Lundin, 1995; Fang et al., 2010). Some studies also make it possible to model the present  
103 and past contributions of these mechanisms to atmospheric escape (Chassefière & Leblanc, 2004).  
104 Combining MEX observations and sophisticated global model simulations, Diéval et al. (2012) have  
105 shown that the precipitating protons originate from both the solar wind and the planetary exosphere.  
106 Here, we use model to simulate the potential effects of the solar dynamic pressure on the ion  
107 precipitation.

108 In this paper, we further analyze the role of the solar dynamic pressure on the ion precipitation by  
109 performing a detailed analysis of MAVEN measurements combined with the simulation of its potential  
110 effects. The LATMOS Hybrid Simulation (LatHyS) model (Modolo et al, 2016) is used to constrain the  
111 processes that may control the ion precipitation. The instruments and data used to perform this

112 analysis, as well as the methodology developed are described in section II. The model is described in  
113 section III whereas section IV present the main results and lessons derived from the  
114 simulation/measurement comparisons and section V the conclusions.

115

## 116 II. MAVEN measurements of the solar wind conditions and precipitating ion flux

### 117 A. Instruments and Data

118 The large set of MAVEN instruments (Jakosky et al. 2015) allows us to characterize the precipitating  
119 ion flux as well as the upstream solar wind conditions and also to constrain the atmospheric and plasma  
120 properties of the Martian environment. In this study, we use measurements performed by the Solar  
121 Wind Ion Analyzer (SWIA; Halekas et al., 2015), the SupraThermal and Thermal Ion Composition  
122 (STATIC; McFadden et al., 2015), the Magnetometer (MAG; Connerney et al., 2015a; 2015b) and the  
123 Solar Extreme Ultraviolet Monitor (EUVM; Eparvier et al., 2015). The MAVEN/SWIA instrument is an  
124 energy and angular ion spectrometer. In this work, we use the SWIA coarse survey data product,  
125 covering an energy range between 25 eV/q and 25 keV/q with 48 energy steps logarithmically spaced,  
126 a field of view (FOV) of  $360^\circ \times 90^\circ$  with 64 angular bins and 4s time resolution. The MAVEN/STATIC  
127 instrument is an energy, mass and angular ion spectrometer. We used the STATIC “D1” data product,  
128 covering an energy range between 0.1 eV/q and 35 keV/q with 32 energy steps logarithmically spaced,  
129 a field of view (FOV) of  $360^\circ \times 90^\circ$  on 64 angular bins and 8 mass bins covering a mass range from 1  
130 amu to 80 amu with a 4s time resolution.

131 We mainly based our study on MAVEN/SWIA despite the lack of mass resolution because  
132 MAVEN/STATIC operates mostly in conic mode (McFadden et al. 2015) below 350 km in altitude  
133 leading to a limited coverage for ions with energy larger than 650 eV. In the following, we use  
134 MAVEN/STATIC to refine our analysis for energies below 650 eV. Moreover, in order to avoid any  
135 potential bias in the measurement due to spacecraft charging, we only consider precipitating ions with  
136 energies larger than 30 eV. Although MAVEN/SWIA does not have mass resolution, it can be used to  
137 estimate the evolution of heavy ion precipitation for the high energy range. Pickup ions can be

138 accelerated by the motional electric field up to a maximum energy limit (Jarvinen and Kallio, 2014;  
139 Rahmati et al., 2015) which is:

$$140 \quad E_{max}(M^+) = 4 * m_M * U_{SW}^2 * \sin^2(\theta_{UB}) = 4 * E_{SW} * \left(\frac{m_M}{m_p}\right) * \sin^2(\theta_{UB}) \quad (1)$$

141 Where  $M^+$  is the species with a mass  $m_M$  and  $\theta_{UB}$  is the angle between the solar wind velocity and the  
142 interplanetary magnetic field,  $m_p$  is the proton mass and  $E_{SW}$  is the energy of the solar wind proton.  
143 The maximum energy is 4 times that of the solar wind, that is, typically around four times 800 eV to 1  
144 keV for nominal conditions for planetary protons and four times 2.4 keV to 4 keV for planetary helium  
145 ions. Therefore, any ions precipitating with energy larger than few keV are most probably planetary  
146 ions with masses larger than the proton and helium masses.

147 The MAVEN/EUVM measures the solar irradiance in three bands from the soft X-ray to the EUV range  
148 (in three spectral bands 0.1-7 nm, 17-22 nm and 121-122 nm) with a temporal resolution of 1s. To  
149 characterize the solar EUV irradiance, we use MAVEN/EUVM channel A which measures solar  
150 irradiance between 17 and 22 nm.

151 The solar wind density, solar wind velocity, and Interplanetary Magnetic Field (IMF) vectors are  
152 measured by MAVEN/SWIA and MAVEN/MAG and averaged on an orbit-by-orbit basis while MAVEN  
153 is in the pristine solar wind (Halekas et al., 2017). In this work, we use the Mars Solar Electric (MSE)  
154 coordinate system in which the X-axis points toward the Sun, the Z-axis is aligned with the solar wind  
155 motional electric field and the Y-axis completes the right hand system (Fedorov et al., 2006).

156

## 157 **B. Upstream and planetary conditions**

158 To investigate the dependence of the precipitating ion flux with respect to the solar wind dynamic  
159 pressure, we used the method developed by Dong et al. (2017) and Martinez et al. (2019b). In absence  
160 of permanent solar wind monitoring, we assume that the averaged solar wind parameters, measured  
161 by MAVEN when inside the solar wind, are constant during the whole orbit as explained in Martinez et



162 al. (2019b). Solar wind parameters on an orbit-by-orbit basis, when MAVEN was in the solar wind, are  
 163 then used to determine the average solar wind parameters for a given set of measurements.  
 164 We organize MAVEN data into two sets of measurements corresponding to two different solar wind  
 165 dynamic pressure conditions: a low dynamic pressure case with values between 0.3 and 1.0 nPa and a  
 166 high dynamic pressure case with values between 1.0 and 2.6 nPa. The IMF strength ( $B_{IMF}$ ) is also  
 167 imposed between 2.2 and 6.7 nT. The solar wind dynamic pressure is defined as  $P_{dyn} = m_p n_{SW} V_{SW}^2$ ,  
 168 where  $m_p$  is the mass of the proton,  $n_{SW}$  and  $V_{SW}$  the solar wind density and velocity. For both sets of  
 169 measurements, we determine the mean solar wind conditions and calculate the norm of the solar wind  
 170 motional electric field defined as  $E = |\overrightarrow{V_{SW}} \times \overrightarrow{B_{IMF}}|$ , the solar wind particle flux defined as  $F_{SW} =$   
 171  $n_{SW} V_{SW}$ , the Alfvén Mach number defined as  $M_A = \frac{V_{SW}}{V_A}$  (with the  $V_A$  the Alfvén speed), the magneto-  
 172 sonic Mach number  $M_{MS}$  as defined in Edberg et al., (2010) and the MSE angle as defined in Martinez  
 173 et al., (2019a). The MSE angle corresponds to the anticlockwise angle between the MAVEN's location  
 174 in MSE coordinates during its measurements of the precipitating ion flux and the East MSE direction  
 175 (MSE longitude equal to  $+180^\circ$  and latitude equal to  $0^\circ$ ).

176

177 These parameters are displayed in Table 1. The last column of Table 1 presents the coverage  
 178 distribution, as defined in Martinez et al, (2019b), showing the percentage of common distribution for  
 179 a given parameter between the two dynamic pressure groups. Except for the solar wind density and  
 180 flux, and obviously for the dynamic pressure, all solar wind properties show similar variations with  
 181 about 70 %, or more, of the distribution of each of these parameters in common. In other words, the  
 182 EUV irradiance, IMF intensity, Alfvén and magnetosonic Mach numbers, solar wind speed and MSE  
 183 angle are similar during these two sets of measurements. The spatial coverage of the ion precipitation  
 184 measurements, characterized by the MSE angle and the solar zenith angle, is also similar during these  
 185 two sets of measurements.

186

187 The presence of crustal magnetic fields (Acuña et al., 1999; Connerney et al., 2005) can influence locally  
 188 the precipitating ion flux, as shown by Hara et al. (2017b). In order to limit the potential influence of  
 189 the crustal fields (Leblanc et al. 2017; Hara et al. 2017b), we also only consider measurements  
 190 performed when the average magnetic field between 200 and 350 km was less than 60 nT. Moreover,  
 191 to further limit the potential role of the crustal fields on the precipitation, we also consider only  
 192 MAVEN measurements performed when the main crustal field region (centered at 180° GEO East  
 193 longitude and -50° GEO latitude) was in the nightside, meaning when the subsolar point has a GEO  
 194 longitude from -60° to 60°.

195

		High Pdyn [1.0,2.6] nPa	Low Pdyn [0.3,1.0] nPa	Common coverage (%)
EUV Flux ( $mW \cdot m^{-2}$ )	$\mu \pm \sigma$	0.22 ± 0.04	0.22 ± 0.03	85.5
	Q25	0.19	0.20	
	Q75	0.24	0.23	
Dynamic pressure ( $nPa$ )	$\mu \pm \sigma$	1.44 ± 0.41	0.63 ± 0.19	0.0
	Q25	1.13	0.46	
	Q75	1.63	0.79	
Solar Zenith Angle (°)	$\mu \pm \sigma$	96 ± 28	96 ± 28	89.7
	Q25	80	77	
	Q75	115	118	
Electric field ( $mV \cdot m^{-1}$ )	$\mu \pm \sigma$	1.44 ± 0.55	1.04 ± 0.45	68.6
	Q25	1.00	0.74	
	Q75	1.77	1.20	
IMF ( $nT$ )	$\mu \pm \sigma$	3.90 ± 1.12	3.23 ± 0.95	69.1
	Q25	2.92	2.50	
	Q75	4.52	3.60	
Speed ( $km \cdot s^{-1}$ )	$\mu \pm \sigma$	448 ± 80	423 ± 78	80.1
	Q25	376	370	
	Q75	495	467	
Density ( $cm^{-3}$ )	$\mu \pm \sigma$	4.67 ± 1.93	2.25 ± 0.97	40.9
	Q25	3.28	1.49	
	Q75	5.69	2.78	
MSE angle(°)	$\mu \pm \sigma$	178 ± 110	203 ± 110	86.2
	Q25	94.7	153	

	Q75	263	322	
Alfven Mach number	$\mu \pm \sigma$	$11.5 \pm 3.0$	$9.1 \pm 2.5$	68.9
	Q25	9.3	7.3	
	Q75	13.1	10.8	
Magnetosonic Mach number	$\mu \pm \sigma$	$7.76 \pm 1.36$	$7.10 \pm 1.38$	86.4
	Q25	6.83	6.10	
	Q75	8.58	8.07	
Solar wind flux ( $10^8 \text{ cm}^{-2}\text{s}^{-1}$ )	$\mu \pm \sigma$	$1.98 \pm 0.62$	$0.91 \pm 0.29$	23.5
	Q25	1.57	0.68	
	Q75	2.36	1.09	

196 **Table 1:** Mean  $\mu$ , standard deviation  $\sigma$ , first quartile Q25 and third quartile Q75 of the solar zenith  
197 angle and each solar planetary parameter distribution for the two sets of precipitating flux  
198 measurement. The last column provides the percentage of the area in common between the two  
199 distributions.

200

### 201 **C. MAVEN's ion precipitation measurements**

202 In order to reconstruct the precipitating ion energy flux, we use the method developed by Leblanc et  
203 al. (2015) and Martinez et al (2019a). We use MAVEN observations of the two sets of measurements  
204 performed between 200 and 350 km. Within such altitude range, any ions moving toward the planet  
205 in a cone of less than  $75^\circ$  with respect to the local nadir direction has a very large probability to impact  
206 Mars' atmosphere. Therefore, to reconstruct the precipitating flux, we sum all measurements of SWIA  
207 (and STATIC) anodes with a FOV corresponding to a cone of less than  $75^\circ$  from the local zenith  
208 direction. Moreover, in order to exclude the reconstructed precipitating flux with poor coverage, we  
209 only consider measurements during which the total FOV of SWIA (and STATIC) anodes covers more  
210 than 65 % of the  $75^\circ$  solid angle cone centered on the zenith direction. In the case of MAVEN/SWIA  
211 measurements, which has a low signal-to-noise ratio at high energy, we adapted the method from  
212 Martinez et al. (2019a) to remove an average background induced by Solar Energetic Particles (SEP).

213 Compared to MAVEN/SWIA, MAVEN/STATIC is less sensitive to SEPs because its measurements  
214 technique is based on double coincidence (McFadden et al., 2015). In case of intense SEP events or  
215 background level, STATIC measurements with poor quality were flagged and systematically excluded  
216 from our analysis. So, the background level of MAVEN/STATIC is assumed to be negligible.

217

218 In this study, MAVEN observations obtained from June 4<sup>th</sup>, 2015 to July 20<sup>th</sup>, 2017 have been  
219 categorized into two groups with similar spatial coverage: high dynamic pressure with 1.44 nPa  
220 averaged on 226 ion precipitation spectra by MAVEN/SWIA, and low dynamic pressure with 0.63 nPa  
221 averaged on 454 ion precipitation spectra by MAVEN/SWIA.

222

### 223 III. LatHyS Model

224

225 In order to simulate the Martian environment and the precipitating heavy ion flux, we choose to use  
226 the hybrid approach which describes ions with a kinetic approach while the electrons are treated as a  
227 fluid (Modolo et al. 2016). The hybrid model called LatHyS is a 3-D multispecies parallelized model that  
228 simulates the interaction of the solar wind plasma with the neutral environment of the planet,  
229 characterizing all plasma regions in the vicinity of the planet. A detailed description of the LatHyS  
230 model can be found in Modolo et al. (2005 and 2016). The model uses as inputs a 3-D density  
231 description of H, O and CO<sub>2</sub> representing the thermosphere and exosphere. The neutral species  
232 description is modeled from the LMD - Global Circulation Model (Forget et al, 1999; Chaufray et al.  
233 2014) and the Exospheric Global Model (Yagi et al, 2012; Leblanc et al, 2017). The state of the neutral  
234 environment corresponds to solar longitude Ls = 270°. The spatial resolution of the LatHyS results  
235 presented in this paper is  $\Delta x = 57$  km, and a mean solar activity is assumed for all the models (LatHyS,  
236 EGM, LMD-GCM) and for the two solar wind dynamic pressure cases.

237

238 Simulations are set up with typical solar wind parameters based on the orbit-by-orbit average solar  
239 wind parameters for the two groups of solar wind dynamic pressure, from Table 1. To facilitate the  
240 interpretation of the simulated precipitation fluxes, the interplanetary magnetic field is taken with only  
241 a  $B_y$  component. For the period of high dynamic pressure we have:  $n_{SW} = 4.7 \text{ cm}^{-3}$ ,  $V_{SW} =$   
242  $450 \text{ km.s}^{-1}$  and  $B_y = 4.0 \text{ nT}$ . For the period of low dynamic pressure we have:  $n_{SW} = 2.2 \text{ cm}^{-3}$ ,  
243  $V_{SW} = 424 \text{ km.s}^{-1}$  and  $B_y = 3.2 \text{ nT}$ . Simulations are performed with a sub-solar longitude at  $0^\circ$   
244 and a subsolar latitude at  $-23^\circ$ , meaning that the main crustal field region is located in the nightside.  
245 To further analyze simulation results, for each particle we record the information of the injection  
246 position, the ionization mechanism of the particle, the injection time, the precipitation time and its  
247 precipitating energy. Three main sources of ions are implemented in the simulation model. A simplified  
248 set of ionospheric chemistry equations is included (below 350 km) and particles created in this region  
249 are labeled as ionospheric particles. Particles can also be produced by photo-ionization above 350 km,  
250 where the optical depth is negligible, or undergo charge exchange reactions. Information concerning  
251 the ionization processes are detailed in Modolo et al. (2016).

252

253 In this study, we consider only oxygen ions. Heavier ions (such as  $Ar^+$ ,  $O_2^+$  and  $CO_2^+$ ) are not considered  
254 because of their much lower density at high altitude according to Fox (2004) so that their contribution  
255 to atmospheric sputtering should be very limited in intensity. Once a steady state of the simulation is  
256 achieved,  $O^+$  ion precipitating ( $V_r < 0$ ) below 250 km in altitude are recorded in order to construct an  
257 energy flux map on a  $4.5^\circ \times 4.5^\circ$  longitude-by-latitude grid. To have meaningful statistics on the  
258 precipitating  $O^+$  ions, the accumulation is performed over 100 solar wind proton gyro-periods (about  
259 6-7 transit times of the simulation box). Each energy spectra corresponding to the impacting  $O^+$  flux is  
260 computed with an energy resolution of  $\frac{dE}{E} = \sim 17\%$  for energy larger than 2 eV. With more than one  
261 million precipitating numerical particles for each simulation, the modelled sample is large enough to  
262 be statistically significant. The stationarity of the solution has been checked by comparing energy

263 spectra at each grid point of the map for various accumulation intervals. We found a temporal standard  
264 deviation of 15-20 % indicating that the simulation converged to a stable solution.

265

266 In order to compare simulation and observation, a similar methodology to reconstruct the simulated  
267 precipitation as for MAVEN measurements have been used:

268 - For each sequence of observation, the portion of MAVEN trajectory during which the  
269 precipitating flux was measured (between 200 km and 350 km in altitude) is  
270 reconstructed in the simulated MSE reference frame.

271 - The simulated energy spectra of the precipitating flux along each of these portions of  
272 MAVEN trajectory are then reconstructed and averaged. If, for a given energy bin, the  
273 simulated flux is lower than the threshold corresponding to MAVEN/SWIA background,  
274 the simulated precipitated ion energy flux, for this energy bin, is not considered to  
275 calculate the average.

276

#### 277 IV. LatHyS simulated precipitation and MAVEN precipitating measurements

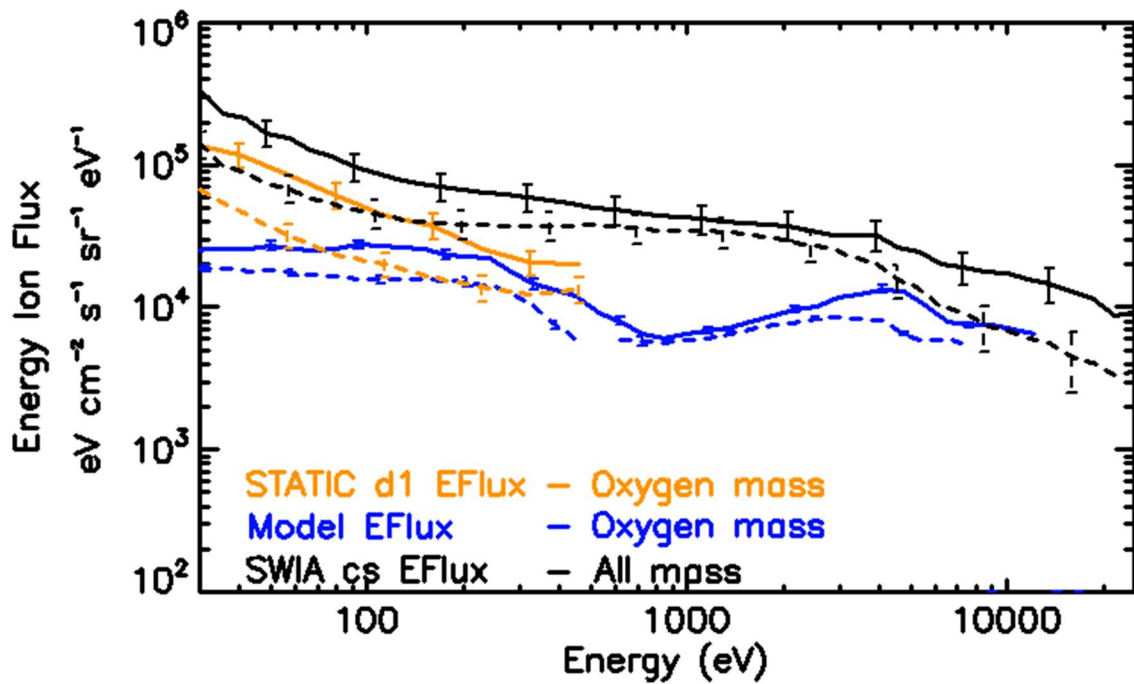
##### 278 A. Comparison between MAVEN observation of the precipitating flux and LatHyS simulated 279 flux

280 Figure 1 shows the comparison of the spectrum of the average precipitating ion energy flux for  
281 MAVEN/SWIA, MAVEN/STATIC and as simulated for the two dynamic pressure cases. The energy  
282 dependence of the differential flux is similar from one solar wind dynamic pressure case to the other  
283 for both instruments. For both dynamic pressure cases, the low-energy component of the precipitating  
284 oxygen ion energy flux measured by MAVEN/STATIC and simulated follow similar dependency with  
285 higher fluxes for larger dynamic pressure. Below 50 eV, we notice an increasing discrepancy between  
286 observation and simulation. This difference can be, in part, explained by the limited resolution of the  
287 simulations (57 km). At low energy, the main component of the oxygen ion precipitation comes from  
288 the ionospheric region (below 350 km in altitude) where the spatial resolution of the simulation

289 remains several times higher than the thermospheric height scale (11-20 km). Because of this, ion  
290 production in the ionosphere (below 350 km in altitude) is probably poorly described, making it less  
291 sensitive to any external variations.

292 For energy larger than a few keVs, as explained in section II.A, MAVEN/SWIA observed ion precipitation  
293 should be in large proportion composed of O<sup>+</sup> ions. Above 3 to 4 keV, there is a clear increase of the  
294 measured and simulated precipitating fluxes from the low dynamic pressure case to the high dynamic  
295 pressure case. The gap between the MAVEN/SWIA curves (all species) and those of the model (only  
296 oxygen ions) between 300 eV and 3-4keV can be explained by the contribution of other species in the  
297 observed ion precipitation (mainly protons, in particular around the solar wind energy, probably  
298 produced in the hydrogen corona).

299 Table 2 shows the integrated precipitating ion energy flux for each dynamic pressure case and two  
300 energy ranges: low energy [30-650] eV) and high energy [650-25000] eV. The ion precipitation  
301 increases when the dynamic pressure of the solar wind increases, as previously observed by Hara et  
302 al. (2017a) with MAVEN/SWIA and MAVEN/STATIC measurements. It increases by a factor between  
303 1.7 and 2.0 at low energy and by factor 1.9 to 2.1 at high energy. Both simulation and observation  
304 agree relatively well when comparing the two dynamic pressure cases, even if the simulation predicts  
305 a systematic factor ~4 lower integrated flux with respect to SWIA observed precipitation for both solar  
306 dynamic pressure cases and energy ranges. At high energy, this factor can be partially explained by the  
307 fact that the modelled precipitating ion energy flux becomes lower than the MAVEN/SWIA background  
308 and so, the energy ion flux is not considerate, which slightly underestimate the modelled ion  
309 precipitation. In other words, even if the simulation did not perfectly reproduce the absolute intensity  
310 of the observed precipitation, the simulated variation of the precipitating flux with increasing pressure  
311 might be driven by a similar mechanism to the one controlling the dependency of this flux in MAVEN  
312 observations.



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Figure 1: Average precipitating ion differential energy spectra as measured by MAVEN/SWIA (black – all species), MAVEN/STATIC (orange – oxygen mass) and simulated (blue – oxygen mass) during high pressure period (line) and low pressure period (dashed line). The vertical lines correspond to the standard error of the average flux.

		Integrated precipitating ion energy flux	
		Low energy [30-650] eV	High energy [650-25000] eV
High pressure period	SWIA (all species)	$4.27 (\pm 0.93) \times 10^7$	$42.8 (\pm 11.1) \times 10^7$
	STATIC	$2.06 (\pm 0.41) \times 10^7$	<del>XXXXXXXXXX</del>
	Model	$1.03 (\pm 0.08) \times 10^7$	$10.8 (\pm 0.6) \times 10^7$
	SWIA	$2.57 (\pm 0.58) \times 10^7$	$22.4 (\pm 7.2) \times 10^7$



<b>Low pressure period</b>	(all species)		
	STATIC	$9.89 (\pm 1.98) \times 10^6$	
	Model	$6.07 (\pm 0.04) \times 10^6$	$5.10 (\pm 0.15) \times 10^7$
<b>Ratio HPDYN/LPDYN</b>	SWIA (all species)	1.66	1.91
	STATIC	2.08	
	Model	1.70	2.12

319 **Table 2:** Integrated precipitating ion energy flux as measured by MAVEN/STATIC (only oxygen ion)  
320 and MAVEN/SWIA (all species) and modelled by LatHyS (only oxygen ion) for each period. The last  
321 three line correspond to the ratio between the high pressure period values and the low pressure  
322 period values for each instrument. In brackets, the 1-sigma standard deviation (uncertainty) of the  
323 precipitating ion energy flux values. The integrated ion precipitation unit is in  $eV \cdot cm^{-2} \cdot sr^{-1} \cdot s^{-1}$ .

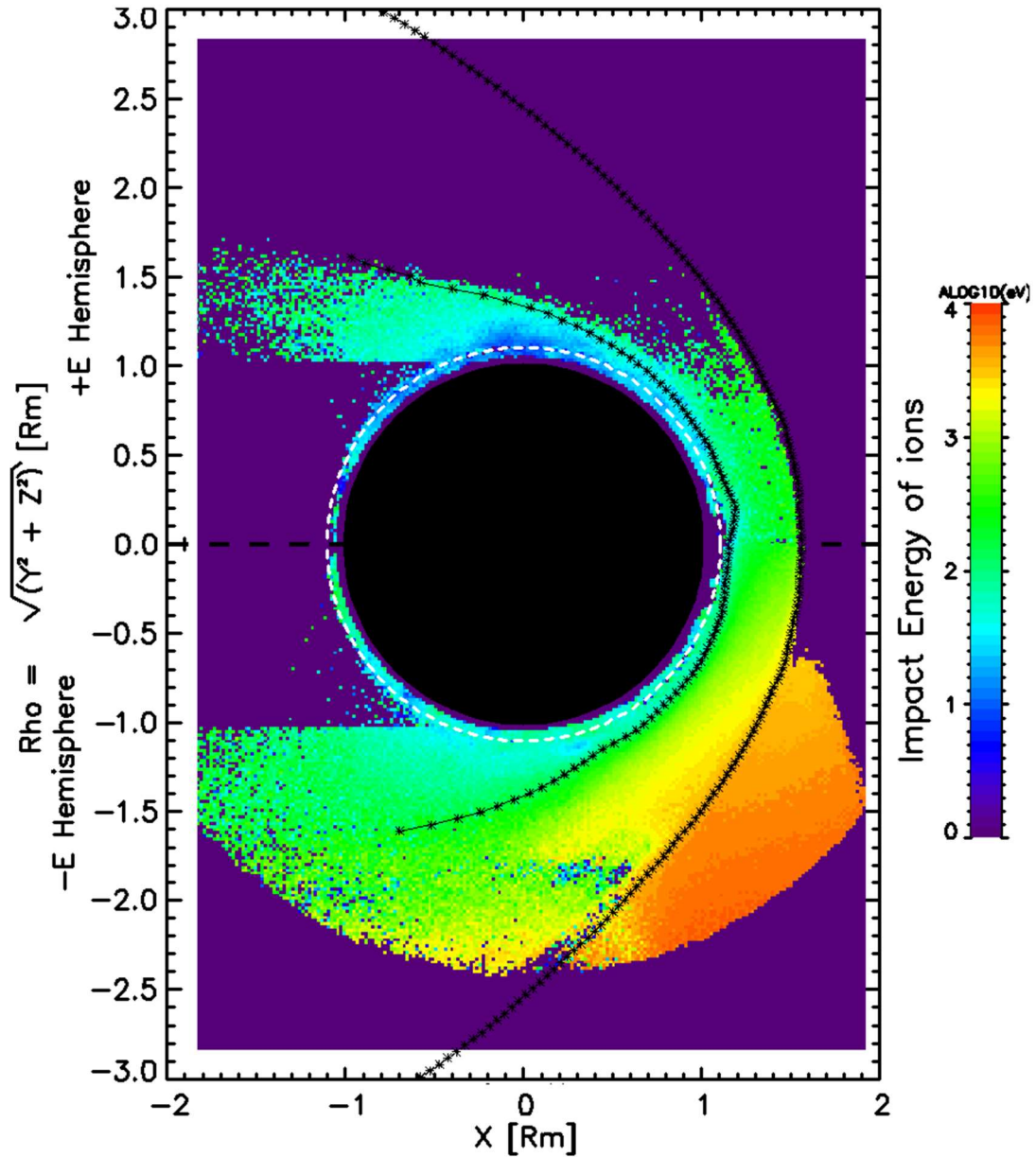
324

### 325 B. Origins and parameters controlling the simulated precipitating fluxes

326 Figure 2 displays the impact energy of the precipitating oxygen ions (of ionospheric origin, created by  
327 photo-ionization or by charge exchange) as a function of their injection (creation) position in the  $(X, \rho)$   
328 coordinate system with  $\rho = \sqrt{Y^2 + Z^2}$ , for the low pressure case. The negative values of  $\rho$   
329 correspond to the Southern Hemisphere MSE ( $Z < 0$ ) while positive values indicate the Northern  
330 Hemisphere ( $Z > 0$ ). The lack of injected particles behind Mars is explained by the shadow of the planet,  
331 preventing photo-ionizations. The precipitating ions with energy higher than the solar wind (800 eV -  
332 1 keV) are formed in the southern hemisphere MSE and their final energy depends on their altitude of  
333 creation (by ionization). This energy-altitude injection relation is consistent with Jarvinen et al. (2018)  
334 and can be explained by the time spent by an ion in the high electric field regions (essentially the solar  
335 wind and the magnetosheath). In the northern hemisphere, it can also be seen that precipitating ions  
336 are mainly formed within or downstream of the pile-up magnetic region. The high-energy ions

337 precipitate mainly in the Southern hemisphere and on the Martian dayside (not shown) as simulated  
338 in Luhmann and Kozyra (1991). This distribution of the origin position of precipitating ions and their  
339 impact energy can be explained by the intensity of the electric field and its direction (Chaufray et al.,  
340 2007; Curry et al., 2015). In the upstream solar wind and the magnetosheath, the newly born ions will  
341 be accelerated in the direction of the convective electric field. Ions formed in the northern hemisphere  
342 MSE will be moved away Mars, while ions formed in the southern hemisphere MSE will be accelerated  
343 toward Mars, as observed in Hara et al. (2017a). This is why for high  $X > 0$  and  $\rho > -0.5$  in Figure 2,  
344 there are almost no precipitating ions formed upstream the bow shock. The ions formed inside the  
345 magnetosheath will see a disturbed electric field direction which may lead them to precipitate. To  
346 summarize, this result indicates that oxygen ions created above the ionosphere in the  $-E$  hemisphere  
347 can more easily precipitate toward the planet rather than those created in the  $+E$  hemisphere, in good  
348 agreement with previous numerical simulations (Chaufray et al., 2007; Fang et al., 2010; Curry et al.,  
349 2015).

350



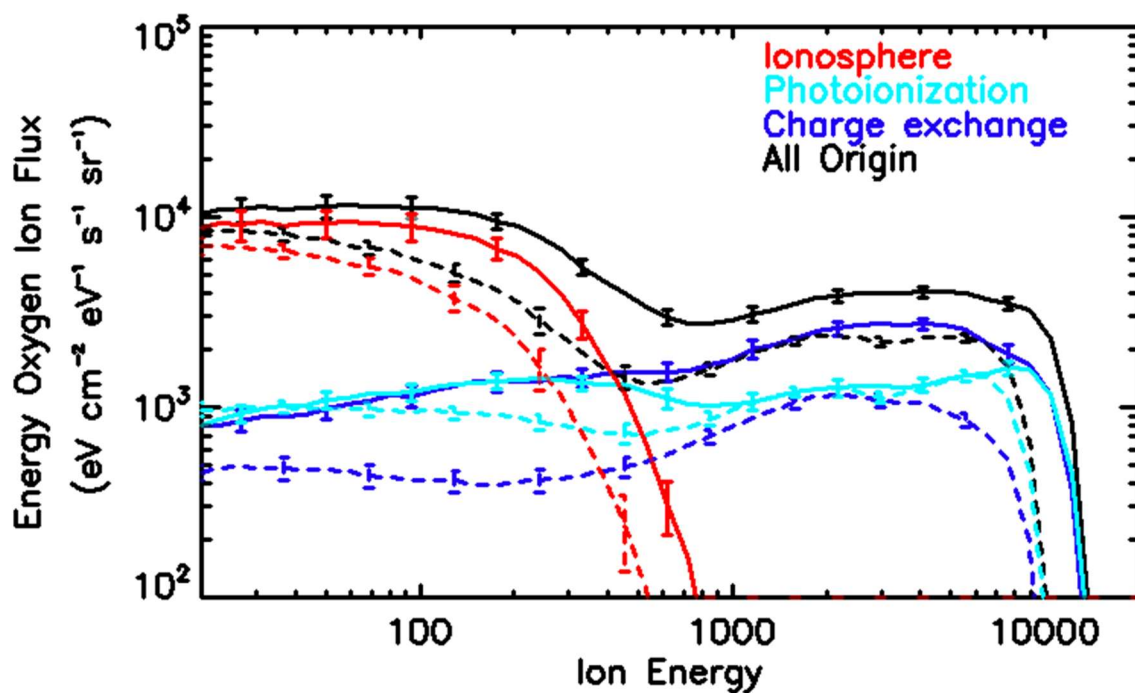
351

352 Figure 2: Map of the origin position of the precipitating ions produced either in the ionosphere (below  
 353 350 km in altitude), by photo-ionization or by charge exchange for the low pressure period. The impact  
 354 energy of the modelled ions is shown in color. The black lines correspond to the ion magnetopause  
 355 boundary (closest to Mars) and bow shock (farthest from Mars) location. The dashed white circle  
 356 corresponds to the upper limit of the ionosphere (350 km in altitude).

357

358 Figure 3 displays the energy distribution of the simulated precipitating oxygen ion energy flux averaged  
 359 over the whole oxygen ion precipitation map (without removing the background value of  
 360 MAVEN/SWIA). In the high dynamic pressure case, the maximum energy of the ions impacting the  
 361 atmosphere reaches 14 keV whereas in the low dynamic pressure case only 10 keV. This illustrates the  
 362 fact that ions created at the same position see a stronger electric field intensity in the case of high  
 363 pressure ( $E = 1.44 \text{ mV} \cdot \text{m}^{-1}$  upstream of the bow shock) than in the case of the low pressure ( $E =$   
 364  $1.04 \text{ mV} \cdot \text{m}^{-1}$  upstream of the bow shock)

365 As a matter of fact, the main difference between the two modelled dynamic pressure cases can be  
 366 described as a global shift in energy, associated with a change in the local electric field intensity, and  
 367 an increase of the intensity of the precipitating ions. As an example, in the case of the ionospheric ions  
 368 (red lines in Figure 3), there is a significant increase of the precipitating flux with increasing dynamic  
 369 pressure above 50 eV, as observed by the MAVEN/STATIC. In the same way, in the case of the ions  
 370 produced by photoionization Figure 3, there is globally an increase in energy of the precipitating ions  
 371 due to the increase of the electric field close to Mars when increasing the dynamic pressure.



372

373 Figure 3: Simulated precipitating oxygen ion differential energy spectra. Solid line: high dynamic  
374 pressure case. Dashed line: low dynamic pressure case. Red lines: oxygen ionospheric ions. Dark blue  
375 lines: oxygen ions produced by charge exchange. Light blue lines: oxygen ions produced by photo-  
376 ionization. Black lines: total precipitating oxygen ions flux. Vertical lines: standard deviation of the flux  
377 estimated by performing several snapshots during the simulation.

378

379 However, in the case of the ion produced by charge exchange, a higher dynamic pressure induces not  
380 only a gain of energy of the precipitating particle but also an increase in the charge exchange ionization  
381 rate between solar wind protons and O atmospheric neutral particles which should be proportional to  
382 the solar wind particle flux  $\sim n_{SW}V_{SW}$ . The ionization rate by charge exchange should increase by a  
383 factor  $\sim 2.3$  which is the ratio between the solar wind flux in the high dynamic pressure case to the  
384 solar wind flux in the low dynamic pressure case. This ratio is very close to the ratio of the precipitating  
385 fluxes of the ions produced by charge exchange between the high and low dynamic pressure cases  
386 (equal to  $\sim 2.7$ ). On the other hand, the production rates of ion in the ionosphere or by photo-ionization  
387 are not or only in a limited way influenced by the change of the solar wind dynamic pressure. As shown  
388 in Figure 3 in the case of the high dynamic pressure (dark blue line), the precipitating flux is dominated  
389 by ions produced by charge exchange above 1 keV. In the low dynamic pressure case, charge exchange  
390 and photo-ionization produces roughly the same amount of ions according to the simulation.

391 The main lessons from the simulation are:

- 392
- 393 - An increase of the dynamic pressure should lead to a global increase of the energy of  
394 the ion precipitating in the atmosphere, roughly proportionally with the change of the  
395 motional electric field in the undisturbed solar wind.
  - 396 - An increase of the dynamic pressure should lead to an increase of the charge exchange  
397 rate in a proportion roughly equivalent to the increase in solar wind flux. This effect  
should be observable at high energy, above typically 1 keV, where the contribution of

398 the charge exchange mechanism on the production of the precipitating ion starts to  
399 dominate.

400 - Below 1 keV, the precipitating ion energy flux should be dominated by the ionospheric  
401 ions which are poorly described by LatHyS due to a limitation in spatial resolution.

402 We also evaluated the impact of the dynamic pressure on the plasma boundaries (essentially on the  
403 bow shock position) by comparing the precipitating flux of oxygen ions produced by photo-ionization  
404 upstream of the bow shock for both cases. With a small difference between the two cases, we  
405 concluded that the precipitating ion flux is only weakly influenced by the compression of the bow shock  
406 with increasing solar dynamic pressure (see supplementary document).

407

## 408 V. Summary and Conclusion

409 Solar wind observations around Mars from the MAVEN spacecraft from 04 June 2015 to 20 July 2017  
410 are organized into two sets of measurements corresponding to two periods of significantly different  
411 solar dynamic pressure. Beside different solar wind conditions, all other parameters that could  
412 potentially influence the state of Mars' atmosphere and magnetosphere are carefully estimated in  
413 order to be equivalent in both samples (by selecting only observations with the same solar conditions  
414 and geographic coverage). From these two periods, we then use MAVEN portions of orbit between  
415 350 and 200 km in altitude to reconstruct the precipitating ion energy fluxes from SWIA (Halekas et al.  
416 2015) and STATIC (McFadden et al. 2015) measurements following the method developed in Leblanc  
417 et al. (2015) and Martinez et al. (2019a).

418 The average solar conditions of each period are then used to simulate Mars' environment using LatHyS  
419 hybrid model (Modolo et al. 2016). These two simulations are realized for the same solar extreme  
420 ultra-violet conditions, the same season of the Martian atmosphere (LS = 270°), with the same  
421 orientation of the Interplanetary Magnetic Field and the main crustal field placed in the nightside. A

422 method is also developed in order to reconstruct the oxygen ion precipitation from both simulations  
423 using the same approach as when analyzing MAVEN measurements.

424 The precipitating ion energy flux measured by MAVEN/STATIC and MAVEN/SWIA increases with the  
425 increase of the solar wind dynamic pressure, which is consistent with previous studies (Hara et al.,  
426 2017a). The increase of the dynamic pressure from 0.63 to 1.44 nPa is clearly associated with an  
427 increase at the same order of the precipitating oxygen ion energy flux measured by MAVEN/STATIC  
428 from  $9.9$  to  $20.6 \times 10^6 \text{ eV} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$  (a ratio of  $\sim 2.1$ ) for the low energy range (from 30 to 650  
429 eV). From 650 eV to 25000 eV, observations by MAVEN/SWIA show an increase from  $22.4$  to  $42.8 \times$   
430  $10^7 \text{ eV} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$  (a ratio of  $\sim 1.9$ ) with a similar order as the increase in solar wind dynamic  
431 pressure.

432 Such increase can be explained, according to the simulation results by several mechanisms. The  
433 increase of the dynamic pressure leads to a global increase of the energy and intensity of the ion  
434 precipitating into the atmosphere. In terms of energy differential precipitating flux, this is equivalent  
435 to a shift in energy of the flux proportional to the increase of the solar wind convective electric field  
436 intensity upstream to Mars, and an increase of the intensity of the energy differential precipitating  
437 flux, proportional to the increase of the solar wind flux because an increase of the solar wind flux also  
438 implies a change of the charge exchange rate between the incident solar wind ions and the planetary  
439 exosphere. Such effect is particularly observable above 1 keV in the simulated precipitating ion energy  
440 flux where the flux is in a large proportion composed of planetary oxygen ions formed by charge  
441 exchange.

442

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449 (<https://pds.nasa.gov/>). Numerical simulation results used in this article can be found in the simulation  
450 database (<http://impex.latmos.ipsl.fr>).

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Figure 1.

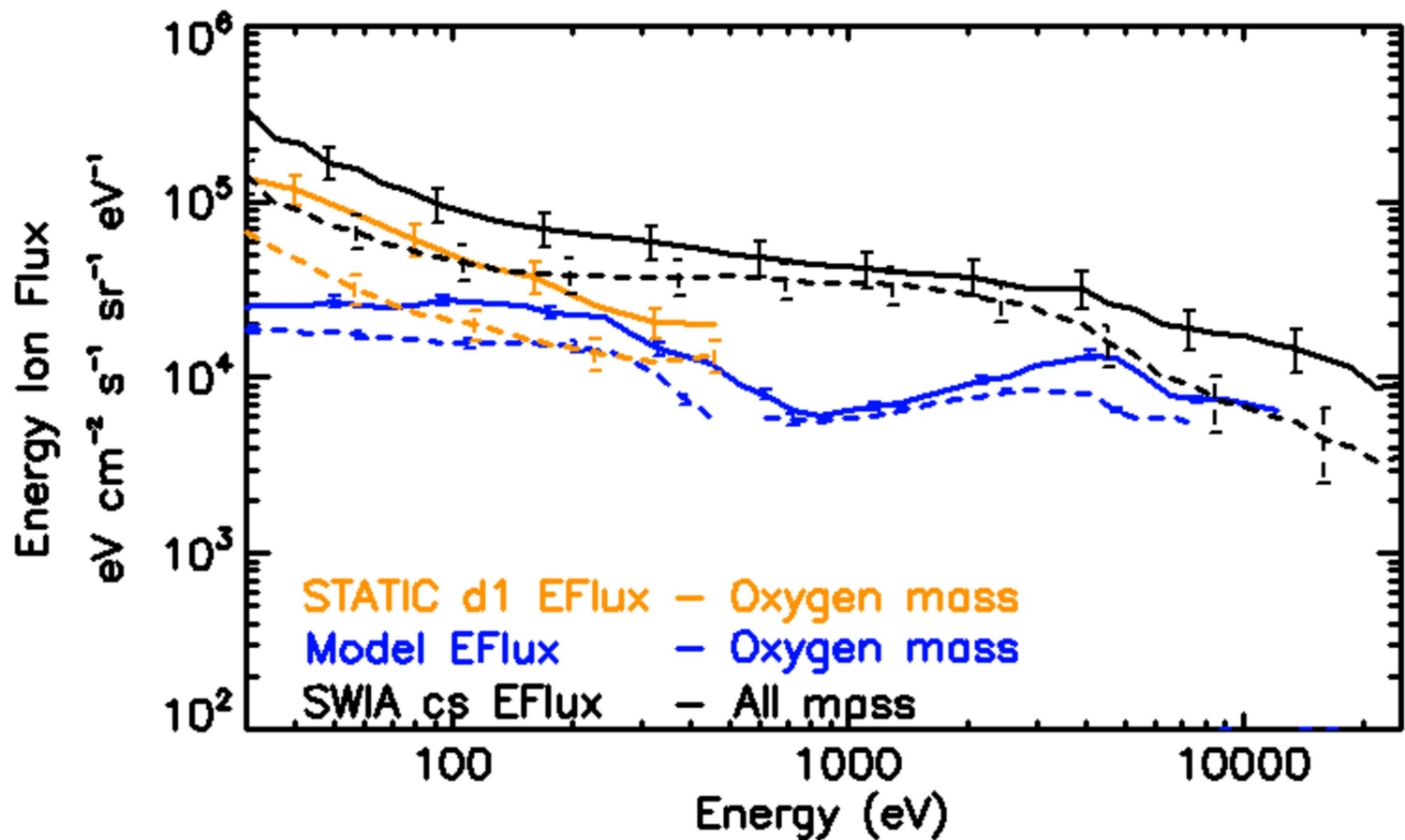




Figure 2.

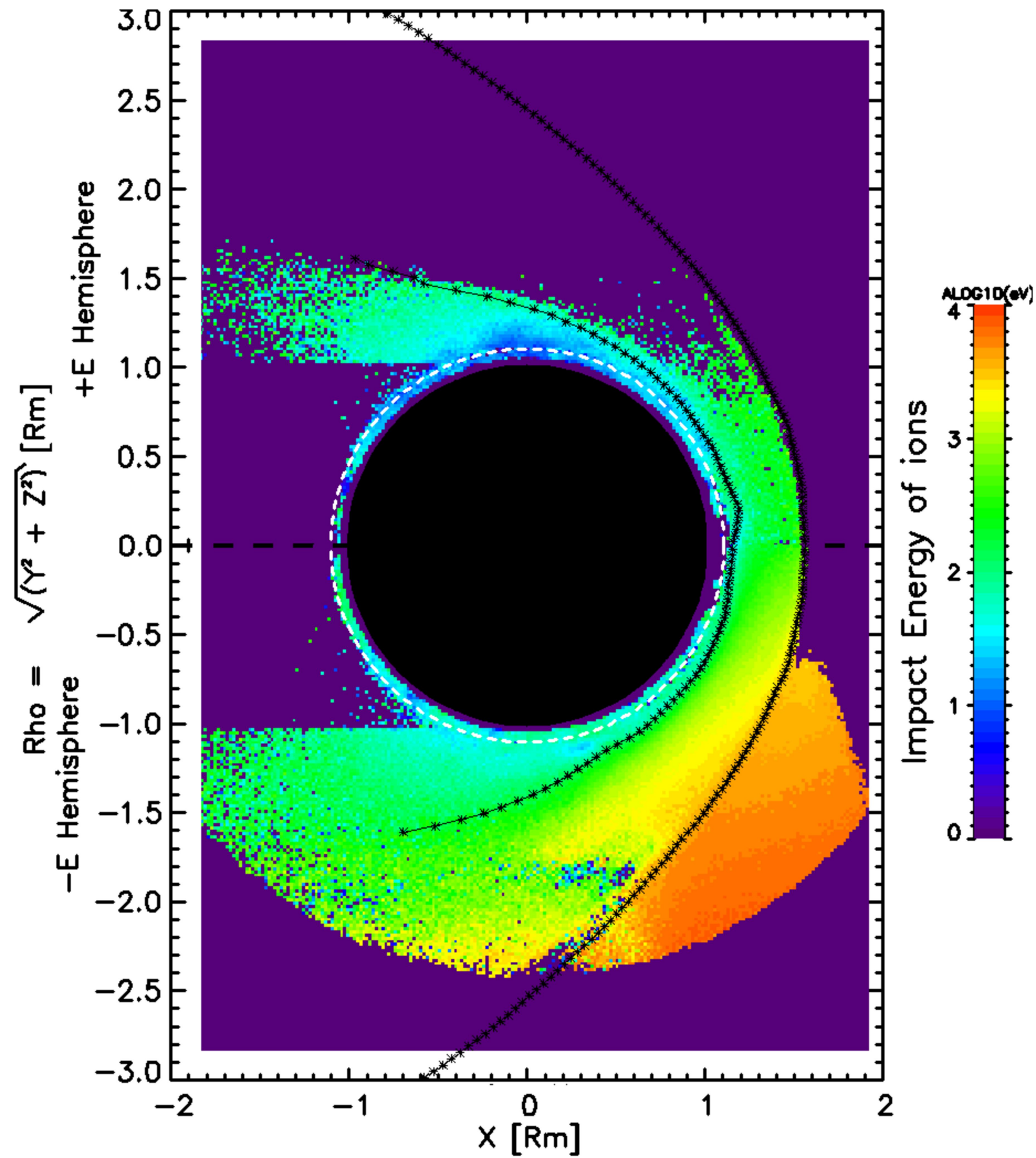


Figure 3.

