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

A. Martinez¹, R. Modolo², F. Leblanc¹, J. Y. Chaufray^{1,2}, O. Witasse³, N. Romanelli⁴, Y. Dong⁵, T. Hara⁶, J. Halekas⁷, R. Lillis⁶, J. McFadden⁶, F. Eparvier⁷, L. Leclercq⁸, J. Luhmann⁶, S. Curry⁶ and B. Jakosky⁷.

¹ LATMOS/IPSL Sorbonne Université, UVSQ, CNRS, Paris, France

² LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France

³ ESTEC, European Space Agency, Noordwijk, Netherlands

⁴ Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA. CRESST II, University of Maryland, Baltimore County, Baltimore, MD, USA.

⁵ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA

⁶ Space Science Laboratory, University of California, Berkeley, CA, USA

⁷ Department of Physics and Astronomy, University of Iowa, IA, USA

⁸ University of Virginia, Charlottesville, VA 22904, USA.

Abstract:

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

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

I. Introduction

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

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

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

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

The statistical study by Hara et al. (2017a) has showed that precipitating ion fluxes observed by MAVEN (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 $10^6 \text{ cm}^{-2} \cdot \text{s}^{-1} \text{sr}^{-1}$ for ions with energies higher than 25 eV) depending on the upstream solar wind conditions such as the dynamic pressure, the magnitude of the interplanetary magnetic field, and the 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 interplanetary magnetic field vector. Indeed, it has been shown by several theoretical studies (Luhmann and Kozyra 1991; Chaufray et al. 2007; Curry et al. 2015) that the orientation of the motional electric field may influence the energy and intensity of ion precipitation on Mars. These studies suggested that the integrated total precipitating ion fluxes are globally larger in the $-\vec{E}$ hemisphere than in the $+\vec{E}$ hemisphere. Pickup oxygen ions formed in the $-\vec{E}$ hemisphere are accelerated towards Mars and can precipitate while oxygen ions formed in the $+\vec{E}$ hemisphere are accelerated away from Mars and can escape. Such results have been observed by Martinez et al. (2019a) and Hara et al. (2017a) thanks to MAVEN.

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

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

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

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

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

A. Instruments and Data

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

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

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

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

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

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

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

B. Upstream and planetary conditions

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

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

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

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

		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 ± 3.0	9.1 ± 2.5	68.9
	Q25	9.3	7.3	
	Q75	13.1	10.8	
Magnetosonic Mach number	$\mu \pm \sigma$	7.76 ± 1.36	7.10 ± 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 ± 0.62	0.91 ± 0.29	23.5
	Q25	1.57	0.68	
	Q75	2.36	1.09	

Table 1: Mean μ , standard deviation σ , first quartile Q25 and third quartile Q75 of the solar zenith angle and each solar planetary parameter distribution for the two sets of precipitating flux measurement. The last column provides the percentage of the area in common between the two distributions.

C. MAVEN's ion precipitation measurements

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

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

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

III. LatHyS Model

In order to simulate the Martian environment and the precipitating heavy ion flux, we choose to use the hybrid approach which describes ions with a kinetic approach while the electrons are treated as a fluid (Modolo et al. 2016). The hybrid model called LatHyS is a 3-D multispecies parallelized model that simulates the interaction of the solar wind plasma with the neutral environment of the planet, characterizing all plasma regions in the vicinity of the planet. A detailed description of the LatHyS model can be found in Modolo et al. (2005 and 2016). The model uses as inputs a 3-D density description of H, O and CO₂ representing the thermosphere and exosphere. The neutral species description is modeled from the LMD - Global Circulation Model (Forget et al, 1999; Chaufray et al. 2014) and the Exospheric Global Model (Yagi et al, 2012; Leblanc et al, 2017). The state of the neutral environment corresponds to solar longitude Ls = 270°. The spatial resolution of the LatHyS results presented in this paper is $\Delta x = 57$ km, and a mean solar activity is assumed for all the models (LatHyS, EGM, LMD-GCM) and for the two solar wind dynamic pressure cases.

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

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

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

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

- For each sequence of observation, the portion of MAVEN trajectory during which the precipitating flux was measured (between 200 km and 350 km in altitude) is reconstructed in the simulated MSE reference frame.
- The simulated energy spectra of the precipitating flux along each of these portions of MAVEN trajectory are then reconstructed and averaged. If, for a given energy bin, the simulated flux is lower than the threshold corresponding to MAVEN/SWIA background, the simulated precipitated ion energy flux, for this energy bin, is not considered to calculate the average.

IV. LatHyS simulated precipitation and MAVEN precipitating measurements

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

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

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

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

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

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	$2.06 (\pm 0.41) \times 10^7$	
	Model	$1.03 (\pm 0.08) \times 10^7$	$10.8 (\pm 0.6) \times 10^7$
	SWIA	$2.57 (\pm 0.58) \times 10^7$	$22.4 (\pm 7.2) \times 10^7$

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

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

B. Origins and parameters controlling the simulated precipitating fluxes

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

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

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

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

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

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

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

The main lessons from the simulation are:

- An increase of the dynamic pressure should lead to a global increase of the energy of the ion precipitating in the atmosphere, roughly proportionally with the change of the motional electric field in the undisturbed solar wind.
- An increase of the dynamic pressure should lead to an increase of the charge exchange 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

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

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

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

V. Summary and Conclusion

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

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

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

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

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

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database (<http://impex.latmos.ipsl.fr>).

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Figure 1.

Figure 2.

Figure 3.