



HAL
open science

Influence of Extreme Ultraviolet Irradiance Variations on the Precipitating Ion Flux From MAVEN Observations

Antoine Martinez, François Leblanc, Jean-Yves Chaufray, Ronan Modolo,
Olivier Witasse, Y. Dong, T. Hara, J. Halekas, R. Lillis, J. Mcfadden, et al.

► **To cite this version:**

Antoine Martinez, François Leblanc, Jean-Yves Chaufray, Ronan Modolo, Olivier Witasse, et al..
Influence of Extreme Ultraviolet Irradiance Variations on the Precipitating Ion Flux From MAVEN
Observations. *Geophysical Research Letters*, 2019, 46 (13), pp.7761-7768. 10.1029/2019GL083595 .
insu-02182513

HAL Id: insu-02182513

<https://insu.hal.science/insu-02182513v1>

Submitted on 16 Dec 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Influence of Extreme Ultraviolet irradiance variations on the precipitating ion**
2 **flux from MAVEN observations.**

3 A. Martinez¹, F. Leblanc¹, J. Y. Chaufray^{1,2}, R. Modolo², O. Witasse³, Y. Dong⁴, T. Hara⁵, J. Halekas⁶, R.
4 Lillis⁵, J. McFadden⁵, F. Eparvier⁶, L. Leclercq⁷, J. Luhmann⁵, S. Curry⁵, D. Titov³ and B. Jakosky⁶.

5
6 ¹ LATMOS/IPSL Sorbonne Université, UVSQ, CNRS, Paris, France

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

8 ³ ESTEC, European Space Agency, Noordwijk, Netherlands

9 ⁴ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA

10 ⁵ Space Science Laboratory, University of California, Berkeley, CA, USA

11 ⁶ Department of Physics and Astronomy, University of Iowa, IA, USA

12 ⁷ University of Virginia, Charlottesville, VA 22904, USA.

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29 **Abstract:**

30 We study the influence of the solar EUV flux intensity on the precipitating ion fluxes as seen by
31 MAVEN/SWIA, an energy and angular ion spectrometer. We defined three periods with significantly
32 different EUV flux intensity (1.6 and 3.2 times the lowest EUV intensity) and compare the
33 precipitating ion flux measured by MAVEN/SWIA during each period. At low energy [30-650] eV, we
34 find that the median (average) precipitating ion flux during the medium and low EUV periods are
35 respectively 1.7 (2.1) and 3 (3.5) times more intense than the flux during the high EUV period. At high
36 energy [650-25000] eV, a similar trend in the intensity of the precipitating ion flux is observed but
37 with an increase by 50% (46%) and 70% (79%) respectively. A larger EUV flux does therefore not
38 seem to favour heavy ion precipitation into Mars' atmosphere, contrary to modelling prediction and
39 overall expectations.

40

41 I. Introduction

42 Mars' upper atmosphere is constantly bombarded by energetic ions from either the solar wind or
43 from Mars' exosphere (planetary pickup ions) (Lillis et al. 2015). Planetary ions created by the
44 ionization of exospheric neutral particles can be accelerated by the motional solar wind electric field.
45 Some of these ions escape (Brain et al. 2016), but a significant portion can impact Mars' atmosphere,
46 leading to collisional cascade in Mars' thermosphere and to the ejection of atmospheric particles into
47 the exosphere (Luhmann and Kozyra, 1991). This process, named "atmospheric sputtering" (Johnson,
48 1994), could have induced a significant atmospheric loss along Mars' history (Luhmann et al., 1992;
49 Leblanc, and Johnson, 2001 and 2002).

50 Atmospheric escape induced by sputtering at present epoch is expected to be small compared to
51 other mechanisms (Leblanc et al. 2017) and so difficult to measure. However, since the main driver
52 of sputtering is ion precipitation (Johnson et al, 2000; Wang et al, 2014;2015), it is crucial to constrain
53 the dependence of the precipitating ion flux on present solar wind conditions. While many studies
54 have been carried out on the influence of the Extreme-Ultraviolet/Ultraviolet (EUV/UV) flux on the
55 Martian environment as well as on ion escape (Modolo et al., 2005; Ma and Nagy, 2007; Terada et al.
56 2009; Edberg et al., 2009; Lundin et al, 2008,2013; Ramstad et al., 2015; Dong et al., 2017), the
57 relation between ion precipitation and EUV flux has only been studied in theoretical works (Chaufray
58 et al., 2007; Leblanc and Johnson, 2002; Wang et al., 2014,2015) and briefly discussed in Nilsson et
59 al., 2012. We therefore describe here the first empirical study on the influence of the EUV flux on ion
60 precipitation by analyzing MAVEN measurements (Jakosky et al. 2015). In section II, we describe the
61 set of data used in this work. In section III, we carefully analyzed the various potential solar wind
62 drivers to extract three sets of measurements obtained during different EUV flux intensity but for
63 similar solar wind conditions and geographical coverage. In section IV, we summarize and discuss the
64 main results of this study and conclude in section V.

65

66 II. Data set used for this analysis

67 We use measurements performed by the Solar Wind Ion Analyzer (SWIA) (Halekas et al., 2015), the
68 Magnetometer (MAG) (Connerney et al., 2015a; 2015b) and the Solar Extreme Ultraviolet Monitor
69 (EUVM) (Eparvier et al., 2015). The MAVEN/SWIA is an energy and angular ion spectrometer covering
70 an energy range between 25eV/q and 25keV/q with 48 energy steps logarithmically spaced, a field of
71 view (FOV) of 360°x90° on 64 angular bins and 4s time resolution. We based our study on
72 MAVEN/SWIA despite the lack of mass resolution because MAVEN/STATIC (which has mass
73 resolution) has much more restricted coverage of the precipitating flux. The MAVEN/EUVM measures
74 the solar irradiance in three bands from the soft X-ray to the EUV range (in three spectral bands 0.1-
75 7nm, 17-22nm and 121-122nm) with a temporal resolution of 1s. The solar wind density, speed, and
76 IMF vector are measured by MAVEN/SWIA and MAVEN/MAG and averaged on an orbit-by-orbit basis
77 in order to characterize the solar wind conditions (Halekas et al., 2017). We then reconstruct the
78 Mars Solar Electric (MSE) coordinate system in which the X-axis is toward the Sun, the Z-axis points
79 along the solar wind motional electric field and the Y-axis completing the right hand system (Fedorov
80 et al., 2006).

81

82 In order to reconstruct the precipitating ion flux, we follow the method described in Leblanc et al.
83 (2015) and Martinez et al (2019). We select all MAVEN measurements performed between 200 and
84 350km. Within such altitude range, any ion which velocity direction is at less than 75° with respect to
85 the local nadir direction has a very large probability to impact Mars' atmosphere. Therefore, to
86 reconstruct the precipitating flux, we sum all measurements of SWIA anodes which FOV is at less
87 than 75° from the local zenith direction. Moreover, in order to exclude reconstructed precipitating
88 flux with poor coverage, we only consider measurements during which the total FOV of SWIA anodes
89 is more than 65% of the 75° solid angle cone centered on the zenith direction.

90 In this study, to characterize the EUV flux during the declining solar cycle from medium to minimum
91 activity, we use the MAVEN/EUVM channel A which measures solar irradiance between 17 and

92 22nm. We sort the MAVEN data from December 2014 to July 2018 into three periods: high EUV
 93 (From 2 December 2014 to 10 March 2015) with an average EUV flux of $0.42\text{mW}\cdot\text{m}^{-2}$, medium EUV
 94 (From 4 June 2015 to 22 October 2015, from 23 December 2015 to 1 June 2016, and from 4
 95 December 2016 to 20 July 2017) with an average EUV flux of $0.21\text{mW}\cdot\text{m}^{-2}$ and low EUV (from 28
 96 November 2017 to 31 July 2018) with an average EUV flux of $0.13\text{mW}\cdot\text{m}^{-2}$. These three intervals
 97 represent several different Mars seasons. Table 1 summarizes the main characteristics of each
 98 period.

99

	High	Medium	Low
[Date begin- Date End] (dd/mm/yyyy)	[02/12/2014- 10/03/2015]	[04/06/2015-22/10/2015] [23/12/2015-01/06/2016] [04/12/2016-30/07/2017]	[28/11/2017 31/07/2018]
Heliocentric distance (AU)	[1.38-1.43]	[1.54-1.66] [1.49-1.66] [1.39-1.63]	[1.40-1.65]
Solar Longitude (LS) °	[244.3°-305.2°] (northern hemisphere winter)	[352.5°-57.9°] [85.1°-161.5°] [273.5°-35.7°] (one Martian year)	[93.4°-221.1°] (northern hemisphere summer and autumn)
Mean EUV flux ($\text{mW}\cdot\text{m}^{-2}$) from channel A of MAVEN/EUVM	0.42	0.21	0.13
Average Precipitating ion flux ($\text{eV}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}\cdot\text{s}^{-1}$) [30,650] eV	$1.18 (\pm 0.11) \times 10^7$	$2.49 (\pm 0.12) \times 10^7$	$4.05 (\pm 0.33) \times 10^7$
Median Precipitating ion flux ($\text{eV}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}\cdot\text{s}^{-1}$) [30,650] eV	0.62×10^7	1.07×10^7	1.83×10^7
Average Precipitating ion flux ($\text{eV}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}\cdot\text{s}^{-1}$) [650,25000] eV	$15.9 (\pm 0.7) \times 10^7$	$23.9 (\pm 0.7) \times 10^7$	$26.9 (\pm 1.1) \times 10^7$
Median Precipitating ion flux ($\text{eV}\cdot\text{cm}^{-2}\cdot\text{sr}^{-1}\cdot\text{s}^{-1}$) [650,25000] eV	11.0×10^7	16.1×10^7	19.7×10^7
Number of measurements	425	1205	374

100 **Table 1:** Summary of each period of our study. In brackets, the 1-sigma standard deviation

101 (uncertainty) of the precipitating ion flux values.

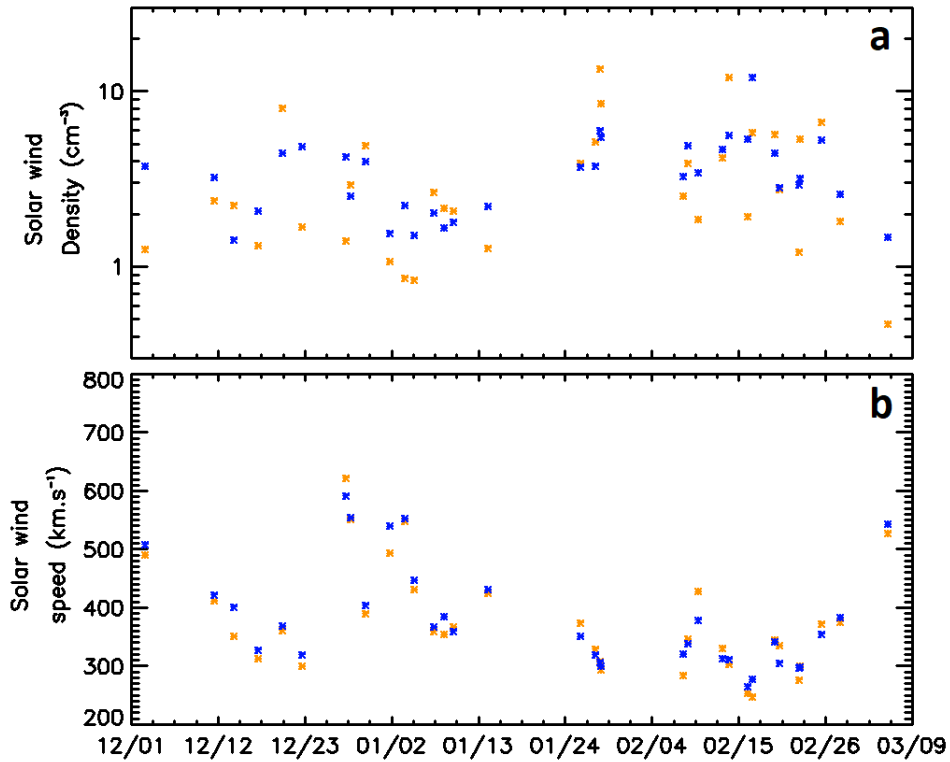
102

103 III. Upstream solar wind conditions and planetary coverage

104 To investigate the Solar EUV dependence of the precipitating ion flux, we first need to reconstruct
105 the solar wind parameters. Lillis et al. (2015), Edberg et al. (2009) and Ramstad et al., (2017)
106 suggested that the dynamic pressure compresses Mars' magnetosphere and favors the acceleration
107 and precipitation of the planetary pickup ions. Martinez et al. (2019) and Hara et al. (2017a) showed
108 that the precipitating ion flux can be organized with respect to the orientation of the solar wind
109 convective electric field. Also, the presence of crustal magnetic fields (Acuña et al., 1999; Connerney
110 et al., 2005) can also influence locally the precipitating ion flux, as shown by Hara et al. (2017b). For
111 each orbit, during which the precipitating flux was measured, we therefore used the part of MAVEN
112 orbit in the solar wind to infer the solar wind. We use such solar wind measurements prior to our
113 precipitating flux measurement if the time difference between the two measurements is less than 4
114 hours and 30 minutes (the MAVEN orbital period). We assume that the solar wind conditions do not
115 change significantly between MAVEN measurements of the solar wind and MAVEN measurements of
116 the precipitating flux (in average 2 hours and 20 minutes).

117

118 In order to verify the validity of this assumption, we compare the solar wind density and speed
119 measurements from Mars Express(MEX)/ASPERA-3 (Barabash et al., 2006) with those measured by
120 MAVEN. Starting from $n_{MAVEN/SW}$ and $V_{MAVEN/SW}$ the solar wind density and speed as measured by
121 MAVEN/SWIA before a measurement of the precipitating flux below 350 km, we determine
122 $n_{MEX/SW}$ and $V_{MEX/SW}$, as measured by MEX/ASPERA-3 (Barabash et al., 2006) when MAVEN's
123 altitude was within the time interval during which SWIA measured the precipitating flux. We only
124 consider ASPERA-3 measurements if the measured density was larger than 0.01cm^{-3} and the quality
125 flag larger than 0.6.



126

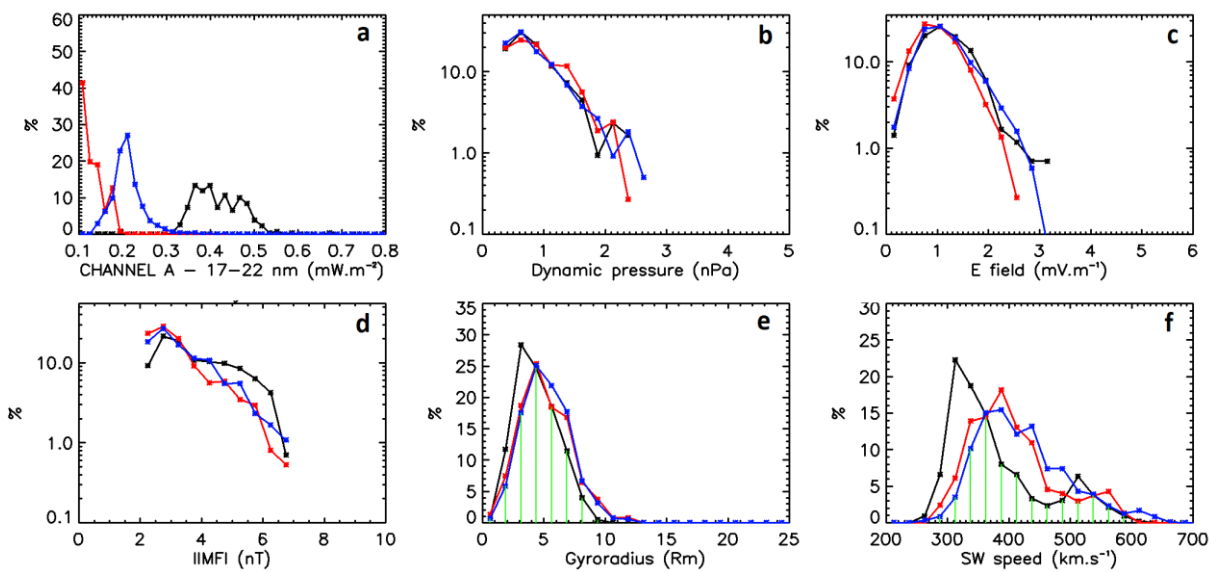
127 *Figure 1: Comparison between the measured solar wind parameters by MAVEN/SWIA (blue) and*
 128 *MEX/ASPERA-3 (orange) for the high EUV period (from December 2014 to March 2015): (a) the*
 129 *solar wind density, (b) Solar wind speed.*

130 With such criteria, we did not identify any measurement for the low EUV period and ASPERA-3
 131 measurements for 4.2% and 8.0% of MAVEN precipitating flux measurements for the medium and
 132 high EUV periods (see also the supplementary materials, Table S.1). The set of measurement
 133 comparisons displayed in Figure 1 for the high EUV period, show that the solar wind speeds as
 134 measured by SWIA and ASPERA-3 are usually in very good agreement (MAVEN: 403 ± 12 km/s and
 135 MEX: 396 ± 12 km/s, for 85 measurements). Contrary to the solar wind speed, the measurements of
 136 the density display a relatively poor agreement (Figure 1b) but still acceptable in an average and
 137 within the one-sigma dispersion (MAVEN: 3.31 ± 0.35 cm⁻³ and MEX: 3.07 ± 0.31 cm⁻³, for 85
 138 measurements).

139 The approach to select the set of measurements used for our study follows the method developed in
 140 Dong et al. (2017). As in Dong et al. (2017), we restrict the set of precipitating measurements to

141 those obtained during solar wind conditions with dynamic pressure $P_{dyn} = m_p n_{SW} V_{SW}^2$, (where m_p
142 is the mass of the proton, n_{SW} and V_{SW} the solar wind density and velocity) between 0.3 and 2.6nPa
143 (moderate solar wind dynamic pressure) and with IMF strength between 2.2 and 6.7nT. We also
144 restrict our sample of precipitation measurements to those obtained in an SZA interval between 70°
145 and 130° . Furthermore, in order to avoid the potential influence of the crustal fields (Leblanc et al.
146 2017; Hara et al. 2017b), we also only consider measurements performed when the average
147 magnetic field between 200 and 350km is less than 60nT. For each set of solar wind parameters, we
148 calculate the solar wind dynamic pressure, the norm of the solar wind motional electric field defined
149 as $E = |\vec{V}_{SW} \times \vec{B}_{IMF}|$ where B_{IMF} is the interplanetary magnetic field (IMF), the Alfvén Mach number
150 $M_A = V_{SW}/V_A$ where V_A is the Alfvén speed, the solar wind flux defined as $F_{SW} = n_{SW}V_{SW}$ and the
151 pickup O^+ gyroradius in the solar wind $R_g = \frac{m_O V_{SW} \sin \theta_{cone}}{q B_{IMF}}$ where m_O is the mass of an O^+ ion,
152 θ_{cone} is the angle between the IMF direction and the MSO X-axis and q is the electron charge value.
153 We also define the MSE angle as the anticlockwise angle between the vector formed by the latitude
154 and the longitude in MSE of the position where the ion precipitation is being measured and the East
155 MSE direction (MSE longitude equal to $+180^\circ$ and latitude equal to 0°) (Martinez et al., 2019).

156



157

158 *Figure 2: Distribution of the set of measured solar wind parameters for the high EUV period*
 159 *(black), the medium EUV period (dark blue) and the low EUV period (red): (a) Values of the EUV*
 160 *photon flux as measured by MAVEN/EUVM instrument, (b) Solar wind dynamic pressure, (c) Solar*
 161 *wind convective electric field, (d) Interplanetary Magnetic Field as measured by MAVEN/MAG, (e)*
 162 *pickup O^+ ion gyroradius calculated in the solar wind and (f) solar wind speed determined by*
 163 *MAVEN/SWIA. The green zone in 2.e and 2.f correspond to the portion of the distribution common*
 164 *to the three periods.*

165

166 In order to demonstrate that the selected sets of measurement for the three EUV periods are similar
 167 in terms of solar wind conditions and planetary geographic coverage (MSO and MSE frames, see also
 168 the supplementary materials, Figures S.1 and S.2), we calculate for each parameter, the area (green
 169 part in Figure 2.e and 2.f) common to the three distributions. The ratio between this common area
 170 and each of the three areas provides a measure of the overlap between the three sets of
 171 measurement for a given solar wind parameter. In Table 2, for 10 solar parameters, we provide the
 172 minimum percentage of the distribution areas in common to the three periods as well as the first and
 173 third quartile, the mean and 1-sigma standard deviation of each parameter.

174 Figure 2 displays the distribution of the values of each of these parameters for the three EUV periods
 175 and illustrates our method to determine the similarity between these sets of measurement. As an
 176 example, in the case of the gyroradius (Figure 2.e), at least 83% of each sets of measurement were
 177 performed for similar values of this parameter. This percentage decreases to 62% for the solar wind
 178 speed (Figure 2.f). On the other hand, the three EUV periods are clearly distinct (Figure 2.a) and
 179 correspond to a null common area (Table 2).

180

		High	Medium	Low	Common coverage (%)
EUV Flux	$\mu \pm \sigma$	0.42 ± 0.08	0.21 ± 0.04	0.13 ± 0.02	0.0

$mW \cdot m^{-2}$	Q25	0.37	0.19	0.11	
	Q75	0.46	0.22	0.14	
Dynamic pressure nPa	$\mu \pm \sigma$	0.87 ± 0.44	0.85 ± 0.46	0.90 ± 0.43	86.0
	Q25	0.56	0.52	0.56	
	Q75	1.08	1.05	1.14	
Electric field $mV \cdot m^{-1}$	$\mu \pm \sigma$	1.18 ± 0.50	1.15 ± 0.51	1.00 ± 0.43	85.4
	Q25	0.83	0.80	0.74	
	Q75	1.48	1.42	1.27	
IMF nT	$\mu \pm \sigma$	3.84 ± 1.16	3.43 ± 1.04	3.25 ± 0.98	74.5
	Q25	2.89	2.59	2.52	
	Q75	4.74	4.06	3.67	
Gyroradius R_g R_{Mars}	$\mu \pm \sigma$	4.36 ± 1.72	5.22 ± 1.94	5.08 ± 2.02	83.2
	Q25	2.87	3.80	3.61	
	Q75	5.51	6.54	6.41	
Alfvén Mach number	$\mu \pm \sigma$	8.89 ± 2.71	9.68 ± 2.71	10.6 ± 3.0	74.2
	Q25	6.87	7.88	8.40	
	Q75	10.1	11.3	12.3	
Speed $km \cdot s^{-1}$	$\mu \pm \sigma$	378 ± 78	422 ± 74	406 ± 70	61.6
	Q25	317	369	353	
	Q75	413	464	443	
Density cm^{-3}	$\mu \pm \sigma$	4.00 ± 2.60	3.02 ± 1.86	3.63 ± 2.25	76.5
	Q25	2.21	1.67	1.89	
	Q75	4.89	3.70	4.99	
Angle MSE (°)	$\mu \pm \sigma$	185 ± 112	202 ± 111	172 ± 115	67.1
	Q25	143	149	38.8	
	Q75	306	326	208	
Solar wind flux $10^8 s^{-1} cm^{-2}$	$\mu \pm \sigma$	1.42 ± 0.77	1.21 ± 0.67	1.38 ± 0.73	79.0
	Q25	0.88	0.72	0.81	
	Q75	1.70	1.50	1.80	

181 **Table 2:** Mean μ , standard deviation σ , first quartile Q25 and third quartile Q75 of each solar
182 parameter distribution for the three sets of precipitating flux measurement. The last column provides
183 the percentage of the area in common between the 3 distributions.

184 If we now only consider the medium and low periods, for all parameters listed in Table 2, the
185 distribution area in common to these two sets of measurement represents more than 75% of each
186 distribution. According to these percentages, we conclude that the three sets of precipitating ion
187 measurements were obtained under similar solar wind conditions.

188

189 To further demonstrate this conclusion, considering the solar wind speed parameter with the less
190 similar distributions between the three periods, we reduce each sample so that the solar wind speed
191 measured during each period was restricted to values between 370 and 500km/s. In that case, the
192 percentage increases to 81%. We then calculate the values of the precipitating ion flux with these

193 reduced samples (see also the supplementary material, Table S.2) and found that all measured
194 precipitating flux values are equivalent for the two different samples except during the medium
195 period when the flux values differ slightly more than one sigma. In another words, the reduction of
196 the sampling improves the similarity between the three sets of measurement and does not change
197 significantly the measured precipitating ion flux

198

199 **IV. Results and Analysis**

200 Our results show that the average ion precipitation decreases when the EUV flux increases (see Table
201 1 and Figure 3). The energy dependence of the differential flux is similar from one period to the
202 other, but we can note that the increase in precipitating ion flux is more significant for energies
203 below 1 to 3 keV than above. This conclusion is not consistent with studies modelling the
204 precipitating ion flux for different solar EUV fluxes (Chaufray et al., 2007) which showed that the flux
205 of O^+ which re-impacts the atmosphere should be smaller at solar minimum than at solar maximum.
206 However, they also concluded that the differences between the two periods were smaller than
207 predicted by Luhmann et al. (1992) using simple gas dynamic description of Mars' interaction with
208 the solar wind. These authors explained this difference by the deceleration of the solar wind due to
209 the mass-loading (Dubinin and Lundin, 1995) which happens further away from Mars at high solar
210 activity and reduces therefore the probability of accelerated pickup ions to re-impact Mars'
211 atmosphere.

212

213 Mass-loading depends to first order on the ionization rate of the Martian exosphere. The exospheric
214 density at a given altitude also depends on the EUV/UV flux which heats the Martian thermosphere
215 whereas the ionization rate directly depends on the solar radiation flux in the wavelength range
216 below 91nm. Forbes et al. (2008) found a very good correlation (0.96) between the long-term EUV
217 flux (proxy F10.7) and the Martian exospheric density at 390km in altitude. Seasonal variations of the
218 exosphere might also significantly impact the density at a given altitude as studied in Bhattacharyya

219 et al, (2015) and Chaufray et al, (2015), as well as the position of the bow shock (Halekas et al, 2017).
220 A peak of exospheric hydrogen density during the Martian dust season was reported by Chaffin et al.
221 (2014), Bhattacharyya et al, (2015) and Halekas (2017) between $L_s=200^\circ$ and 300° . Therefore, an
222 increase in mass-loading of the solar wind might be related to this seasonal variability but would only
223 explain the decrease of the precipitating flux during the high EUV period. During the low and medium
224 periods, there are no significant change in season so that the difference in precipitating flux cannot
225 be associated to seasonal variability.

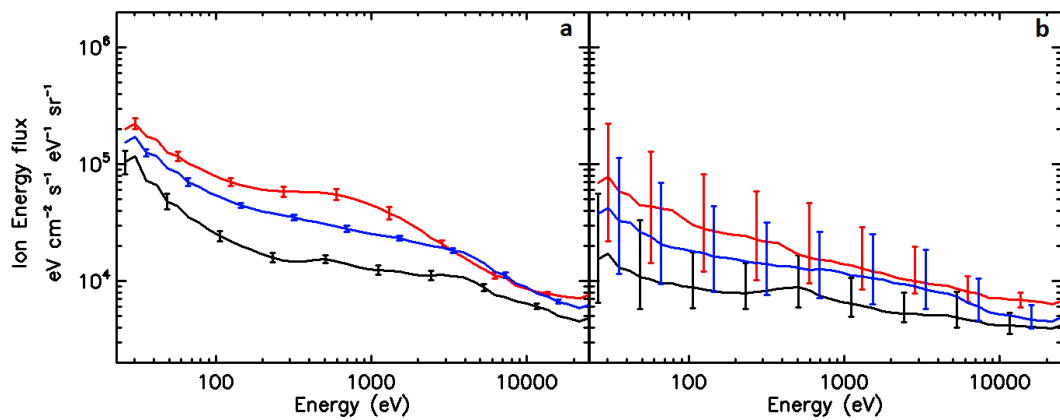
226 As originally suggested by Johnson & Luhmann (1998), an increase of the EUV/UV flux should
227 increase the number of pickup exospheric ions but might also load more efficiently the solar wind
228 and reduce the percentage of these ions able to re-impact the atmosphere. What our study seems to
229 suggest is that this effect might be much more efficient than shown in Chaufray et al. (2007), perhaps
230 due to the limited spatial resolution of their simulation at this time ($\sim 300\text{km}$).

231 Another potential effect is the MSO latitude of the crustal magnetic fields which is solar dependent.
232 Brain et al. (2005) showed that the Magnetic Pile-Up Boundary altitude changes significantly with
233 season because of the latitude variation of the main crustal field structure (centered at 180° GEO
234 East longitude and -50° GEO latitude) along one Martian year. Such effect might be actually due to an
235 increase exospheric hydrogen density rather due to the crustal fields latitudes according to Chaufray
236 et al. (2015). Actually, Hall et al. (2016) shows that an increase in the EUV flux is associated with a
237 position of the bow shock further from Mars, suggesting also an influence of the exosphere on the
238 induced magnetosphere. In any case, we cannot exclude that part of the variation in precipitating
239 flux described here might be due to the crustal field, as actually shown by Hara et al. (2017b). We
240 calculate the average position of the main crustal field structure for the three sets of measurements
241 and found $-47 \pm 17^\circ$, $-45 \pm 16^\circ$, and $-46 \pm 17^\circ$ latitude MSO and $27 \pm 106^\circ$, $-20 \pm 107^\circ$ and
242 $-3 \pm 84^\circ$ longitude MSO for the low, medium and high EUV periods. Therefore, the relative variation
243 of the precipitating ion flux between the three periods selected in our paper might be also related to
244 the variation of the crustal field latitudinal positions. In order to test this possibility, we further

245 reduce our set of measurements in order to only use measurements of the precipitating ion flux
 246 performed when the main crustal field structure was at a SZA larger than 120° . The reconstructed
 247 differential precipitating ion fluxes display very similar relative variation showing, here again, that the
 248 main driver for this variation should be the EUV flux.

249

250 Dong et al. (2017) found that the total escape rate of oxygen ions with $E_i \geq 6$ eV increases by 1.5 when
 251 the EUV flux increases by a similar factor. Our analysis suggested that an increased EUV flux induces a
 252 decrease of the ion precipitation. In the case of the high EUV period (similar to that in Dong et al
 253 (2017)), for the ions with $E_i \geq 25$ eV, we have an integrated precipitating flux equal to $1.3 \times$
 254 10^{22} particles. s^{-1} which should be compared to the estimate by Dong et al. (2017) of an escape
 255 rate of 1.8×10^{24} particles. s^{-1} at $0.2R_{\text{Mars}}$ in altitude. Therefore, the precipitating flux represents
 256 only 1% of the escaping flux in the energy range considered in this paper.



257

258 **Figure 3:** Precipitating ion differential energy spectra as measured by MAVEN/SWIA during high EUV
 259 (black), medium EUV (dark blue) and low EUV periods (red): **(a)** Average value (with 1-sigma standard
 260 deviation) and **(b)** Median value (with first and third quarter).

261

262 **V. Summary and Conclusion**

263 We study the precipitating ion flux from MAVEN instruments over more than three years of data
264 divided into three intervals of solar EUV/UV intensity: between 2 December 2014 and 10 March 2015
265 (Ls from 244.3° to 305.2°), between 4 June 2015 and 1 June 2017 (two Ls periods: from 273.5° to
266 57.9° and from 85.1° to 161.5°) and between 28 November 2017 and 31 July 2018 (Ls from 93.4° to
267 221.1°). By constraining the solar wind conditions, we show that these three samples were obtained
268 under similar solar wind conditions and cover similar regions in a MSE frame.

269
270 We reconstruct the measured precipitating ion flux by MAVEN/SWIA. The increase of the EUV flux
271 intensity from 0.13 to 0.42mW.m⁻² is clearly associated with a decrease of the precipitating ion flux
272 from 18.3 to 6.2 × 10⁶eV.cm⁻².sr⁻¹.s⁻¹ (by almost a factor 3) for the energy range between 30
273 and 650 eV and a decrease by 18% to 44% at higher energies ([650-25000] eV).

274
275 This somewhat surprising result, in contradiction with previous theoretical studies (Chaufray et al.,
276 2007), might illustrate the complex relation between the variations of the exosphere as induced by
277 the solar EUV/UV flux and the solar wind interaction with Mars. Dong et al. (2017) reported an
278 almost linear dependence of the ion escape on the EUV/UV flux, whereas we have found an almost
279 linear anti-correlation between the EUV flux and the precipitating ion flux. In others words, even if
280 the EUV flux increase the ionization rate in the exosphere, the probability of a pickup ion to escape or
281 to precipitate into the atmosphere should also be changed, illustrating a much more complex
282 dependence of the fate of Mars' planetary ions on the solar conditions than anticipated.

283 284 **Acknowledgements**

285 This work was supported by the DIM ACAV and the ESA/ESTEC faculty. This work was also supported
286 by CNES "Système Solaire" program and by the "Programme National de Planétologie" and
287 "Programme National Soleil-Terre". This work is also part of HELIOSARES Project supported by the
288 ANR (ANR-09-BLAN-0223), ANR MARMITE (ANR-13-BS05-0012-02) and ANR TEMPETE (ANR-17-CE31-

289 0016). Data analysis was performed with the AMDA science analysis system provided by the Centre
290 de Données de la Physique des Plasmas (CDPP) supported by CNRS, CNES, Observatoire de Paris and
291 Université Paul Sabatier, Toulouse. All data used in this paper are archived and available in the
292 Planetary Data System Archive.

293

294

295 **References**

296 Acuña, M. H., et al. (1999), Global distribution of crustal magnetization discovered by the Mars
297 Global Surveyor MAG/ER Experiment, *Science*, 284, 790-793, doi:10.1126/science.284.5415.790.

298 Barabash, S., Lundin, R., Andersson, H. et al. *Space Sci Rev* (2006) 126: 113.
299 <https://doi.org/10.1007/s11214-006-9124-8>

300 Bhattacharyya, D., Clarke, J. T., Bertaux, J.-L., Chaufray, J.-Y., and Mayyasi, M. (2015), A strong
301 seasonal dependence in the Martian hydrogen exosphere, *Geophys. Res. Lett.*, 42, 8678– 8685,
302 doi:[10.1002/2015GL065804](https://doi.org/10.1002/2015GL065804).

303 Brain D. A., J. S. Halekas, R. Lillis, D. L. Mitchell, and R. P. Lin, Variability of the altitude of the Martian
304 sheath, *Geophys. Res. Lett.*, 32, L18203, doi:10.1029/2005GL023126, 2005

305 Brain, D. A., F. Bagenal, Y.-J. Ma, H. Nilsson, and G. Stenberg Wieser (2016), Atmospheric escape from
306 unmagnetized bodies, *J. Geophys. Res. Planets*, 121, 2364–2385, doi:[10.1002/2016JE005162](https://doi.org/10.1002/2016JE005162)

307 Chaffin, M. S., Chaufray, J.-Y., Stewart, I., Montmessin, F., Schneider, N. M., and Bertaux, J.-L. (2014),
308 Unexpected variability of Martian hydrogen escape, *Geophys. Res. Lett.*, 41, 314– 320,
309 doi:[10.1002/2013GL058578](https://doi.org/10.1002/2013GL058578).

310 Chassefière, E., and F., Leblanc (2004), Mars atmospheric escape and evolution; interaction with the
311 solar wind, *Planet. Space Sci.*, 52, 1039-1058, doi: 10.1016/j.pss.2004.07.002

312 Chaufray, J. Y., R. Modolo, F. Leblanc, G. Chanteur, R. E. Johnson, and J. G. Luhmann (2007), Mars
313 solar wind interaction: Formation of the Martian corona and atmospheric loss to space, *J. Geophys.*
314 *Res.*, 112, E09009, doi: 10.1029/2007JE002915.

315 J.-Y. Chaufray, F. Gonzalez-Galindo, F. Forget, M.A. Lopez-Valverde, F. Leblanc, R. Modolo, S. Hess
316 (2015), Variability of the hydrogen in the martian upper atmosphere as simulated by a 3D
317 atmosphere–exosphere coupling, *Icarus*, Volume 245, 2015, Pages 282-294, ISSN 0019-1035,
318 <https://doi.org/10.1016/j.icarus.2014.08.038>.

319 Connerney, J.E.P., Açuna, M.H., Ness, N.F., Kletetschka, G., Mitchell, D., Lin, R.P., & Reme, H. (2005).
320 Tectonic implications of Mars crustal magnetism. *Proc. Nat. Acad. Sci.*, Vol. 102, (42), 14970-14975,
321 doi: 10.1073/pnas.0507469102.

322 Connerney, J.E.P., Espley, J., Lawton, P. et al., The MAVEN Magnetic Field Investigation, *Space Sci Rev*
323 (2015a) 195 : 257., <https://doi.org/10.1007/s11214-015-0169-4>

324 Connerney, J.E.P., Espley, J.R., DiBraccio, G.A., et. al. (2015b). First results of the MAVEN magnetic
325 field investigation. *Geophys. Res. Lett.*, 42, 8819–8827, doi:10.1002/2015GL065366.

326 Dong, Y., X. Fang, D. A. Brain, J. P. McFadden, J. S. Halekas, J. E. P. Connerney, F. Eparvier, L.
327 Andersson, D. Mitchell, and B. M. Jakosky (2017), Seasonal variability of Martian ion escape through
328 the plume and tail from MAVEN observations, *J. Geophys. Res. Space Physics*, 122, 4009–4022, doi:
329 10.1002/2016JA023517

330 Dubinin E., Lundin R., Mass-loading near Mars, *Advances in Space Research*, Volume 16, Issue 4,
331 1995, Pages 75-79, ISSN 0273-1177, [https://doi.org/10.1016/0273-1177\(95\)00211-V](https://doi.org/10.1016/0273-1177(95)00211-V).

332 Edberg, N., D. A. Brain, M. Lester, S. W. H. Cowley, R. Modolo, M. Franz, and S. Barabash (2009),
333 « Plasmas boundary variability at Mars as observed by Mars Global Surveyor and Mars Express », *Ann.*
334 *Geophys.*, 27, 3537-3550, doi:10.5194/angeo-27-3537-2009.

335 Eparvier, F.G., Chamberlin, P.C., Woods, T.N. et al., The Solar Extreme Ultraviolet Monitor for
336 MAVEN, *Space Sci Rev* (2015) 195 : 293., <https://doi.org/10.1007/s11214-015-0195-2>

337 Fang, X., S. W. Bougher, R. E. Johnson, J. G. Luhmann, Y. Ma, Y.-C. Wang, and M. W. Liemohn (2013),
338 The importance of pickup oxygen ion precipitation to the Mars upper atmosphere under extreme
339 solar wind conditions, *Geophys. Res. Lett.*, 40, 1922–1927, doi: 10.1002/grl.50415.

340 A. Fedorov, E. Budnik, J.-A. Sauvaud, C. Mazelle, S. Barabash, R. Lundin, M. Acuña, M. Holmström, A.
341 Grigoriev, M. Yamauchi, H. Andersson, J.-J. Thocaven, D. Winningham, R. Frahm, J.R. Sharber, J.
342 Scherrer, A.J. Coates, D.R. Linder, D.O. Kataria, E. Kallio, H. Koskinen, T. Säles, P. Riihelä, W. Schmidt,
343 J. Kozyra, J. Luhmann, E. Roelof, D. Williams, S. Livi, C.C. Curtis, K.C. Hsieh, B.R. Sandel, M. Grande, M.
344 Carter, S. McKenna-Lawler, S. Orsini, R. Cerulli-Irelli, M. Maggi, P. Wurz, P. Bochsler, N. Krupp, J.
345 Woch, M. Fränz, K. Asamura, C. Dierker, Structure of the Martian wake, *Icarus*, Volume 182, Issue 2,
346 2006, Pages 329-336, ISSN 0019-1035, <https://doi.org/10.1016/j.icarus.2005.09.021>.

347 Forbes, J. M., F. G. Lemoine, S. L. Bruinsma, M. D. Smith, and X. Zhang (2008), Solar flux variability of
348 Mars' exosphere densities and temperatures, *Geophys. Res. Lett.*, 35, L01201,
349 doi:[10.1029/2007GL031904](https://doi.org/10.1029/2007GL031904).

350 Halekas, J. S. (2017), Seasonal variability of the hydrogen exosphere of Mars, *J. Geophys. Res.*
351 *Planets*, 122, 901– 911, doi:[10.1002/2017JE005306](https://doi.org/10.1002/2017JE005306).

352 Halekas, J.S., Taylor, E.R., Dalton, G. et al., The Solar Wind Ion Analyzer for MAVEN, *Space Sci Rev*
353 (2015) 195 : 125., <https://doi.org/10.1007/s11214-013-0029-z>

354 Halekas, J. S., et al. (2017), Structure, dynamics, and seasonal variability of the Mars-solar wind
355 interaction: MAVEN Solar Wind Ion Analyzer in-flight performance and science results, *J. Geophys.*
356 *Res. Space Physics*, 122, 547–578, doi: 10.1002/2016JA023167.

357 Hall, B. E. S., et al. (2016), Annual variations in the Martian bow shock location as observed by the
358 Mars Express mission, *J. Geophys. Res. Space Physics*, 121, 11,474–
359 11,494, doi:[10.1002/2016JA023316](https://doi.org/10.1002/2016JA023316).

360 T. Hara, K. Seki, Y. Futaana, M. Yamauchi, M. Yagi, Y. Matsumoto, M. Tokumaru, A. Fedorov, and S.
361 Barabash (2011), Heavy-ion flux enhancement in the vicinity of the Martian Ionosphere during CIR
362 passage: Mars Express ASPERA-3 observations, *JOURNAL OF GEOPHYSICAL RESEARCH*, VOL. 116,
363 A02309, doi:[10.1029/2010JA015778](https://doi.org/10.1029/2010JA015778), 2011

364 Hara, T., et al. (2017a), MAVEN observations on a hemispheric asymmetry of precipitating ions
365 toward the Martian upper atmosphere according to the upstream solar wind electric field, *J.*
366 *Geophys. Res. Space Physics*, 122, 1083–1101, doi: [10.1002/2016JA023348](https://doi.org/10.1002/2016JA023348)

367 Hara T. et al., (2017b), Evidence for crustal magnetic field control of ions precipitating into the upper
368 atmosphere of Mars, *J. Geophys. Res. Space Physics*, 122, doi: [10.1029/2017JA024798](https://doi.org/10.1029/2017JA024798).

369 Jakosky, B.M., Lin, R.P., Grebowsky, J.M. et al., The Mars Atmosphere and Volatile Evolution (MAVEN)
370 Mission, *Space Sci Rev* (2015) 195 : 3. <https://doi.org/10.1007/s11214-015-0139-x>

371 Johnson, R.E., Plasma-induced sputtering of an atmosphere, *Space Sci Rev* (1994) 69: 215.
372 <https://doi.org/10.1007/BF02101697>

373 Johnson, R. E., and J. G. Luhmann (1998), Sputter contribution to the atmospheric corona on Mars, *J.*
374 *Geophys. Res.*, 103(E2), 3649–3653, doi: [10.1029/97JE03266](https://doi.org/10.1029/97JE03266).

375 Johnson, R. E., D. Schnellenberger, and M. C. Wong (2000), The sputtering of an oxygen
376 thermosphere by energetic O⁺, *J. Geophys. Res.*, 105(E1), 1659–1670, doi: [10.1029/1999JE001058](https://doi.org/10.1029/1999JE001058)

377 Leblanc, F. and R.E Johnson (2001), Sputtering of the Martian atmosphere by solar wind pick-up ions,
378 *Planet. Space Sci.*, 49, 645-656, 2001, doi:[10.1016/S0032-0633\(01\)00003-4](https://doi.org/10.1016/S0032-0633(01)00003-4).

379 Leblanc F. and R.E. Johnson (2002), Role of molecules in pick-up ion sputtering of the Martian
380 atmosphere, *J. Geophys. Res.*, <https://doi.org/10.1029/2000JE001473>

381 Leblanc F., R. Modolo and al. (2015), Mars heavy ion precipitating flux as measured by Mars
382 Atmosphere and Volatile Evolution, *Geophys. Res. Lett.*, 42, 9135-9141, doi: 10.1002/2015GL066170.

383 Leblanc F., Chaufray, J. Y., Modolo, R., Leclercq, L., Curry, S., Luhmann, J., ... Jakosky, B. (2017). On the
384 origins of Mars' exospheric nonthermal oxygen component as observed by MAVEN and modeled by
385 HELIOSARES. *Journal of Geophysical Research: Planets*, 122, 2401–2428.
386 <https://doi.org/10.1002/2017JE005336>

387 Leblanc, F. and al., (2018). On Mars' Atmospheric Sputtering after MAVEN first Martian year of
388 Measurements. *Geophysical Research Letters*. doi:10.1002/2018GL077199.

389 Lee, C. O., et al. (2017), MAVEN observations of the solar cycle 24 space weather conditions at Mars,
390 *J. Geophys. Res. Space Physics*, 122, 2768–2794, doi: 10.1002/2016JA023495.

391 Lee, C. O., Jakosky, B. M., Luhmann, J. G., Brain, D. A., Mays, M. L., Hassler, D. M., et al. (2018).
392 Observations and impacts of the 10 September 2017 solar events at Mars: An overview and synthesis
393 of the initial results. *Geophysical Research Letters*, 45. <https://doi.org/10.1029/2018GL079162>

394 Lillis, R.J., Brain, D.A., Bougher, S.W. et al., Characterizing Atmospheric Escape from Mars Today and
395 Through Time, with MAVEN, *Space Sci Rev* (2015) 195 : 357. [https://doi.org/10.1007/s11214-015-](https://doi.org/10.1007/s11214-015-0165-8)
396 [0165-8](https://doi.org/10.1007/s11214-015-0165-8)

397 Luhmann, J. G., and J. U. Kozyra (1991), Dayside pickup oxygen ion precipitation at Venus and Mars:
398 Spatial distributions, energy deposition and consequences, *J. Geophys. Res.*, 96(A4), 5457–5467, doi:
399 10.1029/90JA01753.

400 Luhmann, J. G., R. E. Johnson, M. H. G. Zhang, Evolutionary impact of sputtering of the Martian
401 atmosphere by O⁺ pickup ions, *Geophys. Res. Lett.*, 19, 2151–2154, 1992.
402 <https://doi.org/10.1029/92GL02485>

403 Lundin, R., S. Barabash, M. Holmström, H. Nilsson, Y. Futaana, R. Ramstad, M. Yamauchi, E. Dubinin,
404 and M. Fraenz (2013), Solar cycle effects on the ion escape from Mars, *Geophys. Res. Lett.*, 40, 6028–
405 6032, doi: 10.1002/2013GL058154.

406 Lundin, R., S. Barabash, M. Holmström, H. Nilsson, Y. Futaana, R. Ramstad, M. Yamauchi, E. Dubinin,
407 and M. Fraenz (2013), Solar cycle effects on the ion escape from Mars, *Geophys. Res. Lett.*, 40, 6028–
408 6032, doi: 10.1002/2013GL058154.

409 Ma, Y.-J., and A. F. Nagy (2007), Ion escape fluxes from Mars, *Geophys. Res. Lett.*, 34, L08201, doi:
410 10.1029/2006GL029208.

411 Martinez, A., Leblanc, F., Chaufray, J. Y., Modolo, R., Romanelli, N., Curry, S., et al (2019). Variability
412 of precipitating ion fluxes during the September 2017 event at Mars. *Journal of Geophysical*
413 *Research: Space Physics*, 124. <https://doi.org/10.1029/2018JA026123>

414 McFadden, J.P., Kortmann, O., Curtis, D. et al., MAVEN SupraThermal and Thermal Ion Composition
415 (STATIC) Instrument, *Space Sci Rev* (2015) 195 : 199., <https://doi.org/10.1007/s11214-015-0175-6>

416 Modolo, R., et al. (2016), Mars-solar wind interaction: LathYS, an improved parallel 3-D multispecies
417 hybrid model, *J. Geophys. Res. Space Physics*, 121, 6378–6399, doi: 10.1002/2015JA022324. Ramstad,
418 Nilsson, H., G. Stenberg, S. Futaana, M. Holmstrom, S. Barabash, R. Lundin, N. Edberg, and A. Fedorov
419 (2012), Ion distributions in the vicinity of Mars: Signatures of heating and acceleration processes,
420 *Earth Planets Space*, 64(2), 135–148, doi:[10.5047/eps.2011.04.011](https://doi.org/10.5047/eps.2011.04.011).

421 R., S. Barabash, Y. Futaana, H. Nilsson, X.-D. Wang, and M. Holmström (2015), The Martian
422 atmospheric ion escape rate dependence on solar wind and solar EUV conditions: 1. Seven years of
423 Mars Express observations, *J. Geophys. Res. Planets*, 120, 1298–1309, doi: 10.1002/2015JE004816.

424 Ramstad, R., S. Barabash, F. Yoshifumi, and M. Holmström (2017), Solar wind- and EUV-dependent
425 models for the shapes of the Martian plasma boundaries based on Mars Express measurements, *J.*
426 *Geophys. Res. Space Physics*, 122, 7279–7290, doi:10.1002/2017JA024098.

427 Ronan Modolo, Gérard M. Chanteur, E. Dubinin, A. P. Matthews. Influence of the solar EUV flux on
428 the Martian plasma environment. *Annales Geophysicae*, European Geosciences Union, 2005, 23 (2),
429 pp.433-444. <hal-00329361>

430 Terada, N., Y. N. Kulikov, H. Lammer, H. I. M. Lichtenegger, T. Tanaka, H. Shinagawa, and T. Zhang
431 (2009), Atmosphere and water loss from early Mars under extreme solar wind and extreme
432 ultraviolet conditions, *Astrobiology*, 9(1), 55–70, doi:[10.1089/ast.2008.0250](https://doi.org/10.1089/ast.2008.0250).

433 Wang, Y.-C., J. G. Luhmann, F. Leblanc, X. Fang, R. E. Johnson, Y. Ma, W.-H. Ip, and L. Li (2014),
434 Modeling of the O⁺ pickup ion sputtering efficiency dependence on solar wind conditions for the
435 Martian atmosphere, *J. Geophys. Res. Planets*, 119, 93–108, doi: 10.1002/2013JE004413.

436 Wang, Y.-C., J. G. Luhmann, X. Fang, F. Leblanc, R. E. Johnson, Y. Ma, and W.-H. Ip (2015), Statistical
437 studies on Mars atmospheric sputtering by precipitating pickup O⁺: Preparation for the MAVEN
438 mission, *J. Geophys. Res. Planets*, 120, 34–50, doi: 10.1002/2014JE004660.

439 Xu S. et al., (2018), Investigation of Martian magnetic topology response to 2017 September ICME,
440 *Geophys. Res. Lett.*, 45, doi: 10.1029/2018GL077708.

441

Figure1.

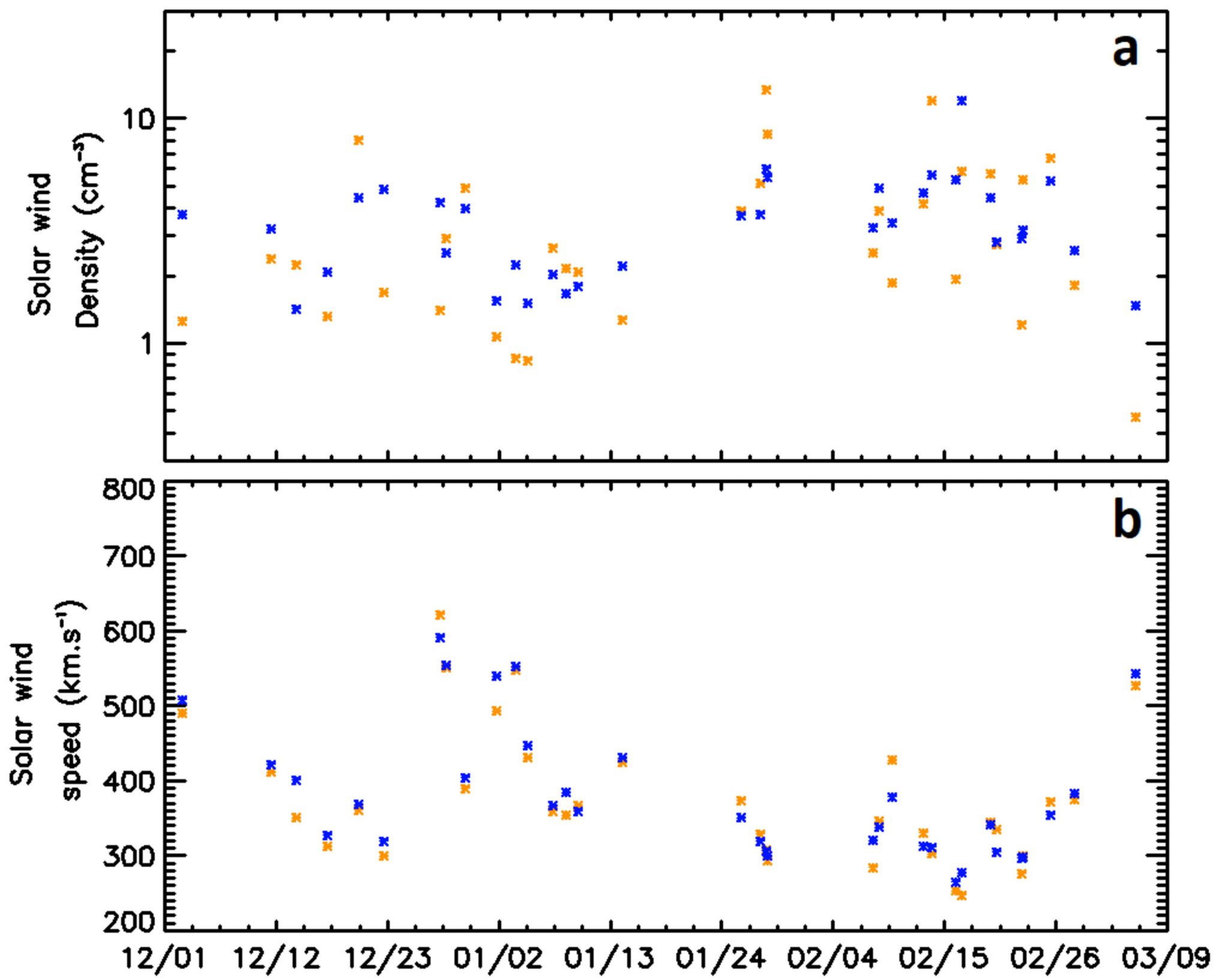


Figure2.

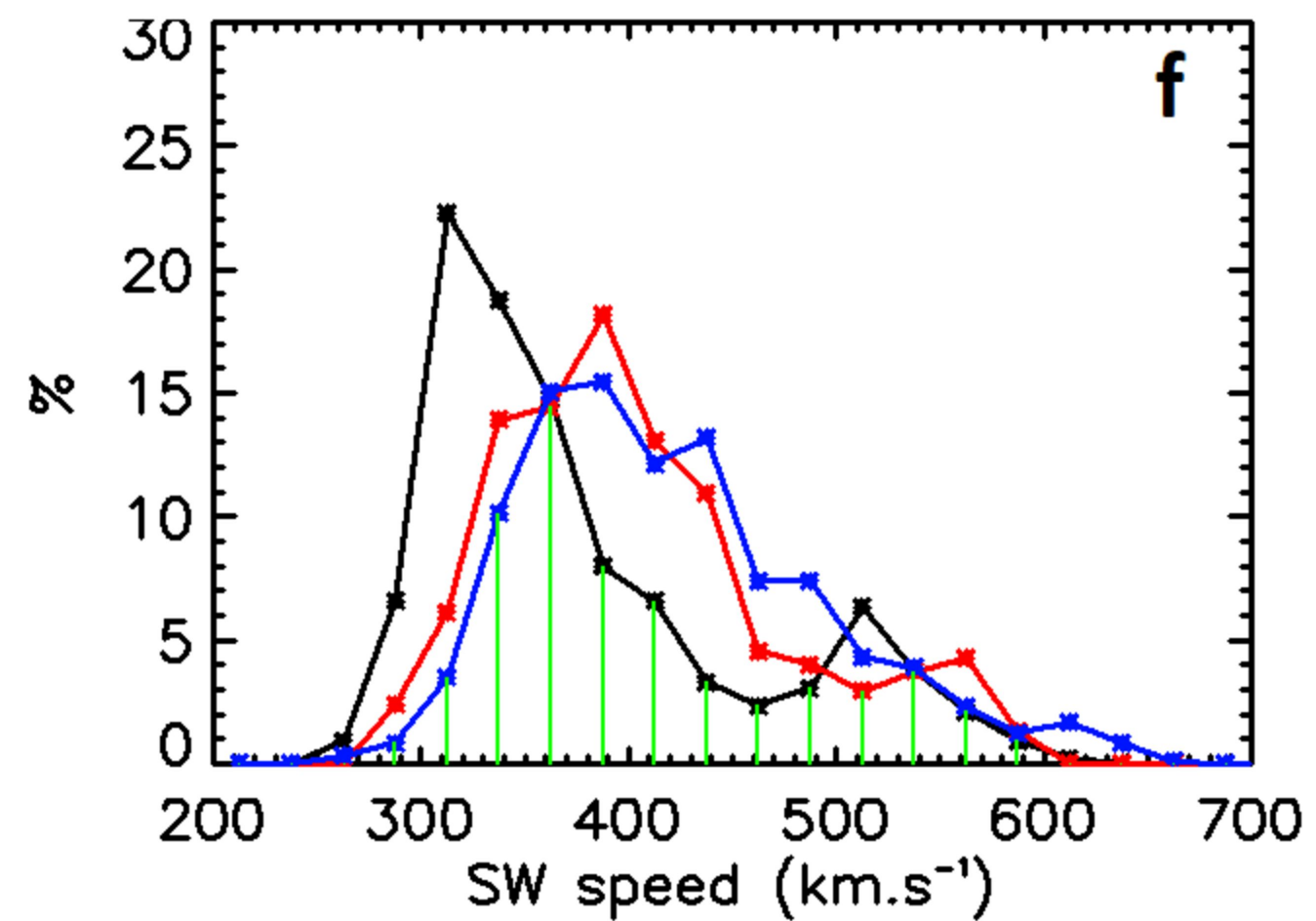
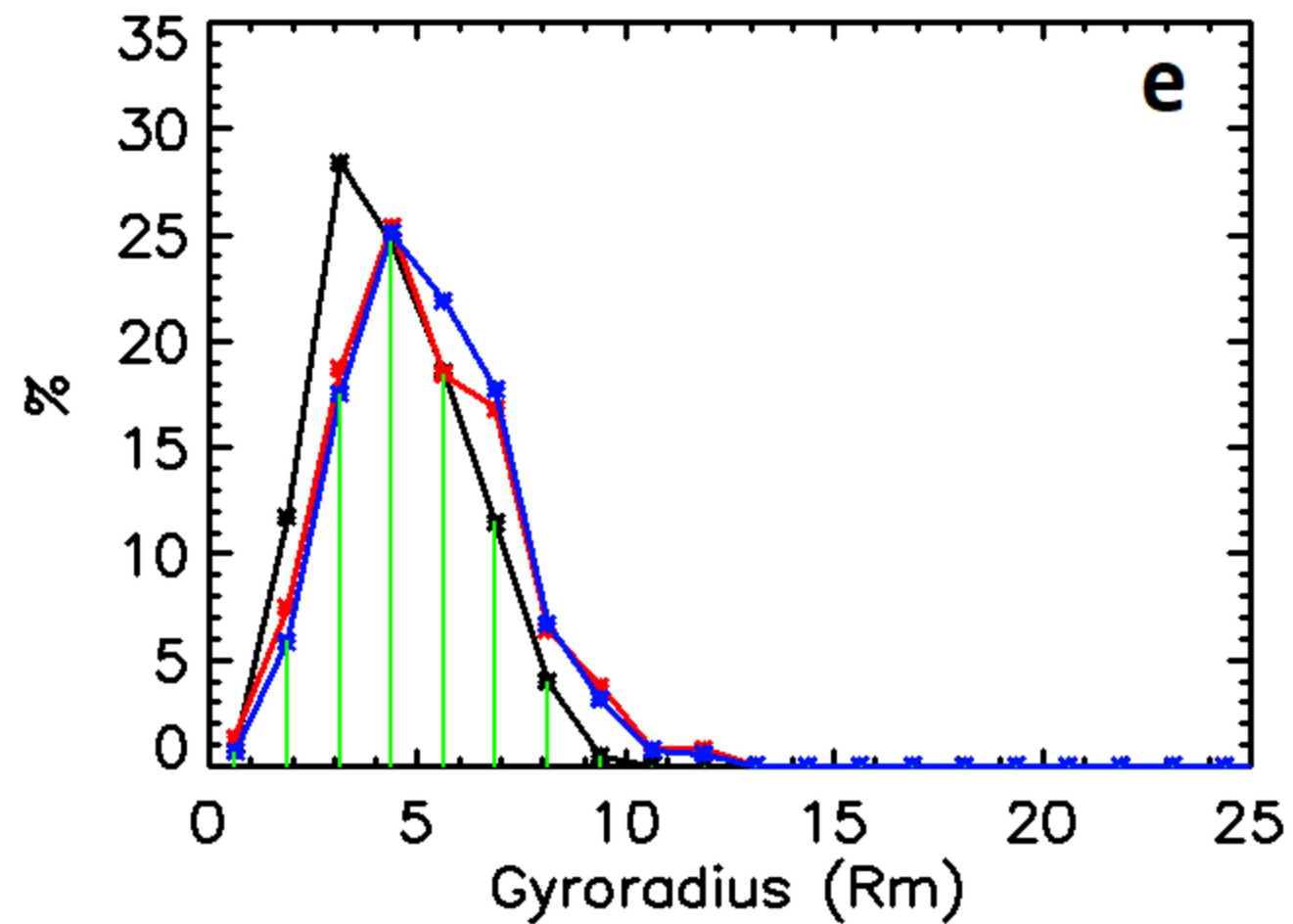
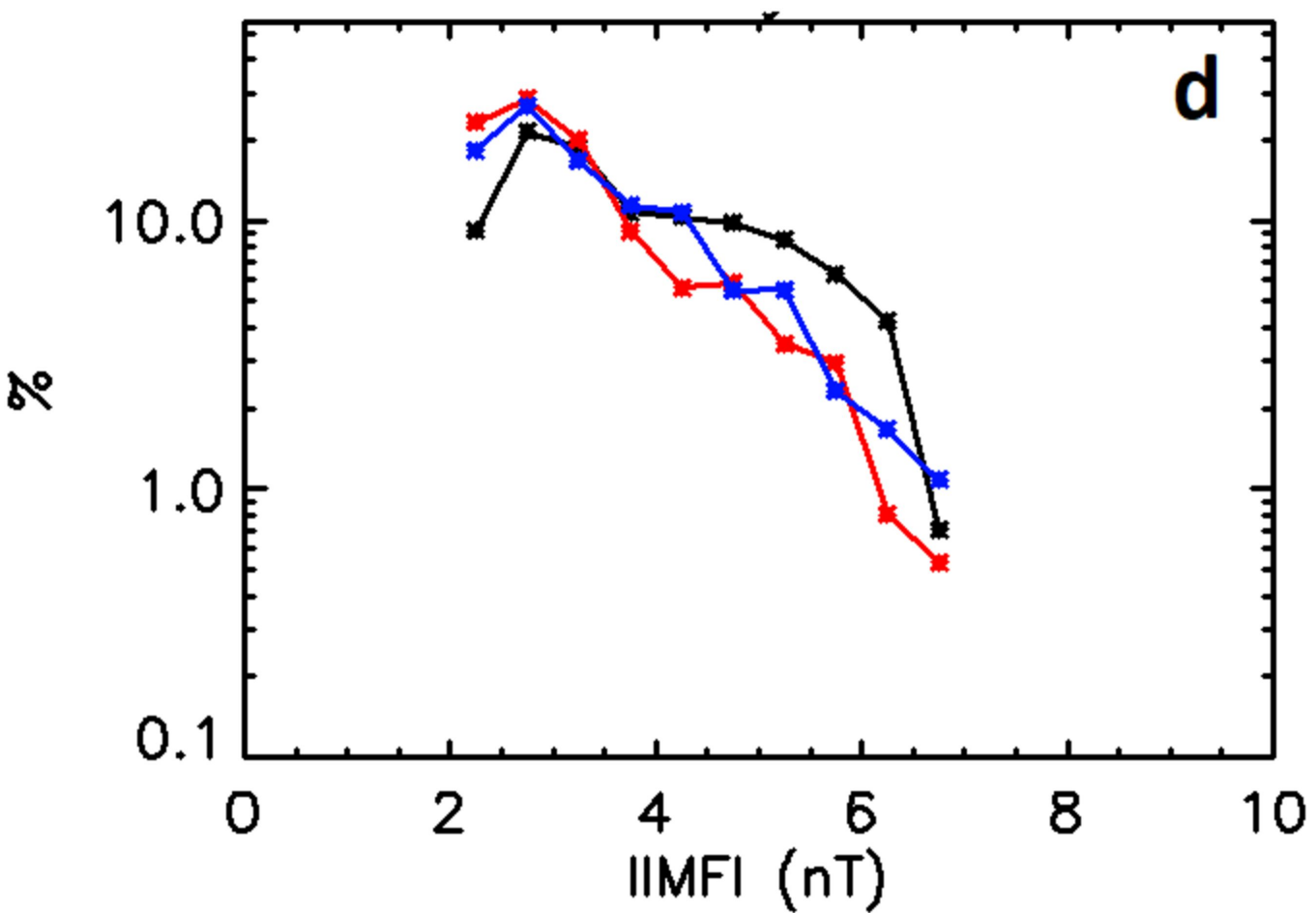
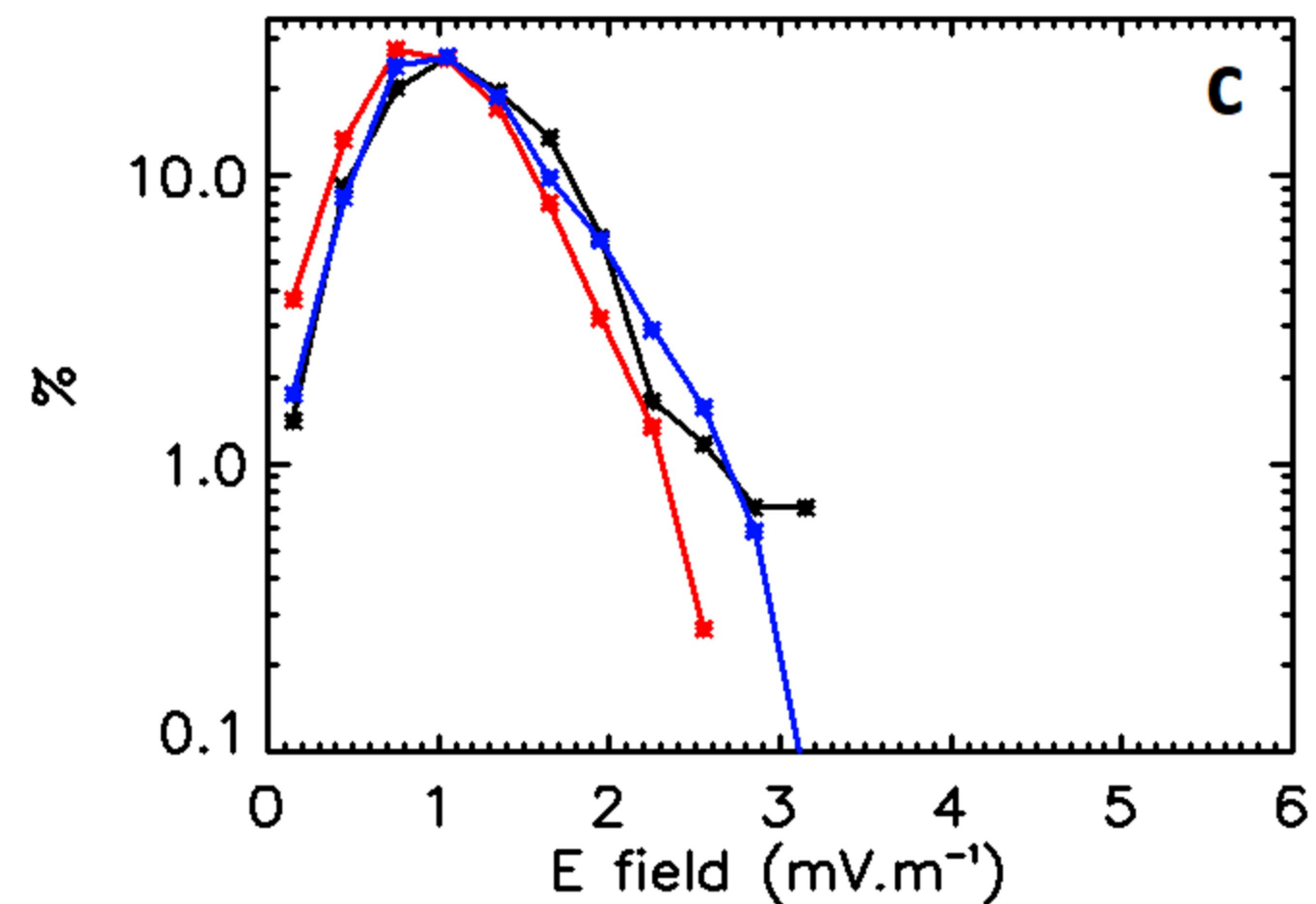
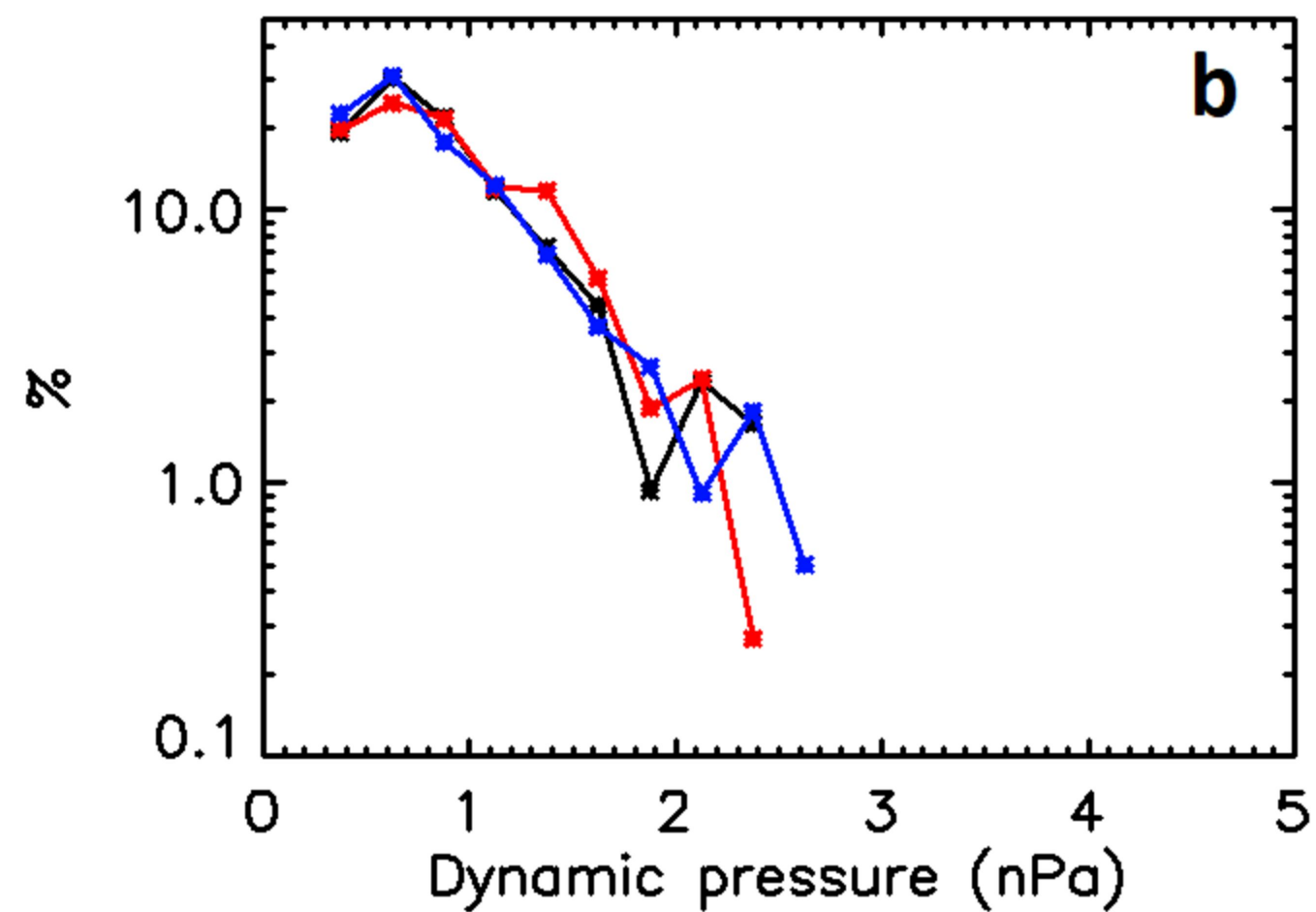
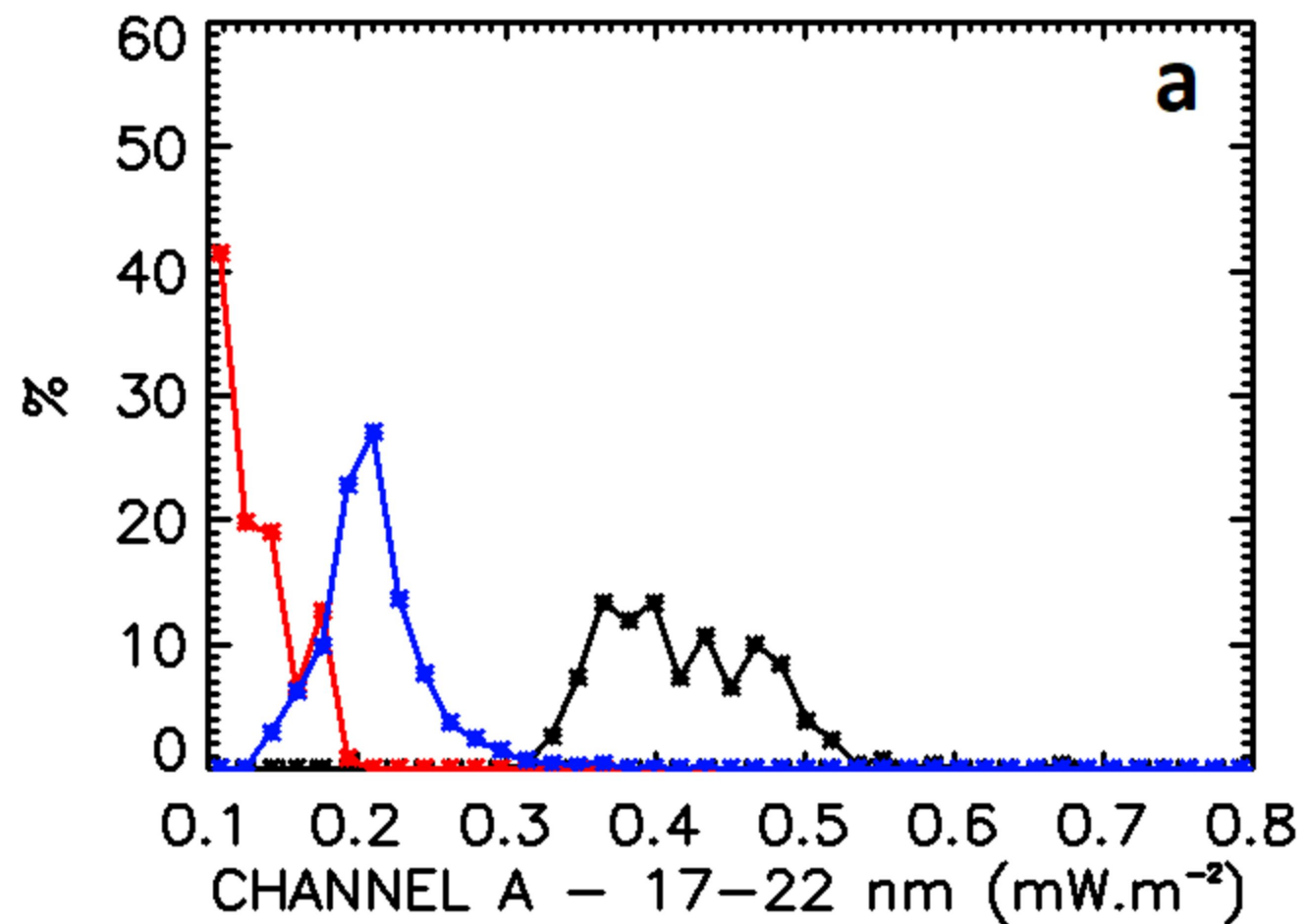


Figure 3.

