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Elisabeth Werner, François Leblanc, Jean-Yves Chaufray, Ronan Modolo, Sae Aizawa, L. Z. Hadid, Claire Baskevitch

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1 **Modeling the impact of a strong X-class solar flare on**  
2 **the planetary ion composition in Mercury's**  
3 **magnetosphere**

4 **A. L. E. Werner<sup>1\*</sup>, F. Leblanc<sup>1</sup>, J. Y. Chaufray<sup>2</sup>, R. Modolo<sup>2</sup>, S. Aizawa<sup>3</sup>, L.**  
5 **Z. Hadid<sup>4</sup>, C. Baskevitch<sup>2</sup>**

6 <sup>1</sup>LATMOS/IPSL, Sorbonne Université, UVSQ, CNRS, Paris, France

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

8 <sup>3</sup>IRAP, Toulouse, France

9 <sup>4</sup>Laboratoire de Physique des Plasmas (LPP), CNRS, Observatoire de Paris, Sorbonne Université,  
10 Université Paris Saclay, Ecole polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France

11 **Key Points:**

- 12 • A strong X-class flare can boost the photoionization frequencies of Mercury's Mg,  
13 O and He exospheres with 40 – 80%.
- 14 • The dayside magnetosphere contains two ion populations for each species which  
15 respond to the flare on different time scales.
- 16 • Depending on the flare geometry, there may be a time delay between the maxi-  
17 mum Mg<sup>+</sup>, O<sup>+</sup> and He<sup>+</sup> ion densities in the magnetosphere.

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\*Current affiliation: Swedish Institute of Space Physics, Uppsala, Sweden

Corresponding author: Elisabeth Werner, [elisabeth.werner@latmos.ipsl.fr](mailto:elisabeth.werner@latmos.ipsl.fr)

**Abstract**

We model the impact of an extreme solar flare on the  $\text{Mg}^+$ ,  $\text{Na}^+$ ,  $\text{O}^+$  and  $\text{He}^+$  ion density distribution in Mercury's magnetosphere. The Flare Irradiance Spectral Model of the solar irradiance during the X9.3-class flare on 6 September 2017 is used as input to the time-dependent Latmos Ionized Exosphere ion density model. We find that the time-evolution of the planetary ion distribution differs with respect to energy, location and species. There exist two ion energy populations on the dayside that experience different dynamical evolution. The peak ion density in the nightside plasma sheet is delayed by  $\sim 7 - 8$  minutes compared to the dayside. The maximum  $\text{Mg}^+$  density occurs  $\sim 4$  minutes before  $\text{He}^+$  and  $\text{O}^+$  in the whole magnetosphere. The time delay between different species does not necessarily occur for solar flares that erupt near the apparent solar limb, where the optical depth is large.

**Plain Language Summary**

A solar flare is a sudden outburst on the Sun which releases radiation and energetic particles. The abrupt radiation enhancement can strongly increase the frequency by which neutral atoms in Mercury's thin atmosphere are ionized. We use a model of the flare radiation spectrum and a new ion density model to study how a strong solar flare impacts the distribution of planetary ions in Mercury's magnetosphere. We select the strongest solar flare of solar cycle 24, which occurred on 6 September 2017. We find that the time-evolution of the ion density varies depending on the planetary ion species, the location inside the magnetosphere, the ion energy and the location of the flare on the Sun with respect to Mercury. The maximum  $\text{Mg}^+$  density occurs  $\sim 4$  minutes before  $\text{He}^+$  and  $\text{O}^+$  in the whole magnetosphere. This only happens for solar flares which erupt near the center of the solar disk as seen from Mercury. There are two ion populations with different energies on the dayside, and a single ion population on the nightside. For all species, the peak ion density in Mercury's shadow occurs  $\sim 7 - 8$  minutes after the corresponding peak on the dayside.

**1 Introduction**

Mercury has a tenuous, collision-less atmosphere (i.e. a surface-bounded exosphere) that consists of H, He, Na, K, Mg, Ca, Mn, Fe and Al (Broadfoot et al., 1974; Potter & Morgan, 1985, 1986; Bida et al., 2000; McClintock et al., 2008; Bida & Killen, 2017; Ver-vack et al., 2016). The exosphere is maintained over time by different source and loss mechanisms. Mercury's exosphere is mainly sourced from the surface regolith, diffusion of gases from Mercury's interior and surface bombardment by solar wind ions (Killen et al., 2007). The species are released from the regolith into the exosphere by a variety of ejection processes, such as thermal desorption, photon-stimulated desorption, solar wind ion sputtering and meteoroid impact vaporization (Leblanc & Johnson, 2003, 2010; Killen et al., 2007). Neutrals are then lost from the exosphere by thermal (Jeans) escape, acceleration of the atoms by the solar radiation pressure to escape velocity and photoionization.

Mercury has a small magnetosphere that is the result of the interaction between the interplanetary magnetic field (IMF) and the intrinsic dipole magnetic field (Anderson et al., 2011). The magnetospheric ion population mainly consists of solar wind ions, but planetary ions may contribute to as much as 10% of the total ion pressure (Yagi et al., 2010). The planetary ions that exist in Mercury's magnetosphere are primarily sourced from photoionization of the neutral exosphere. The Fast Imaging Plasma Spectrometer (FIPS; Andrews et al., 2007) onboard the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) spacecraft has mapped the distribution of planetary ions in Mercury's magnetosphere.  $\text{Na}^+$ -group (mass-per charge ratio  $m/q = 21 - 30$  amu/e),  $\text{O}^+$ -group ( $m/q = 16 - 20$  amu/e) ions and  $\text{He}^+$  were among the most com-

68 only observed ion species by FIPS inside the magnetosphere (Zurbuchen et al., 2011;  
 69 Raines et al., 2013). The planetary ions were found to be particularly abundant in the  
 70 central plasma sheet on the nightside and near the northern cusp on the dayside (Raines  
 71 et al., 2013).

72 Both Mercury’s exosphere (Burger et al., 2014; Cassidy et al., 2015, 2016; Merkel  
 73 et al., 2017, 2018) and the planetary ion environment (Raines et al., 2013; Jasinski et  
 74 al., 2021) have been shown to vary as a function of true anomaly angle (TAA). Ground-  
 75 based observations of the Na exosphere have shown variations with a timescale on the  
 76 order of hours (Leblanc et al., 2008, 2009; Mangano et al., 2009, 2013, 2015; Orsini et  
 77 al., 2018) to minutes (Masetti et al., 2017). Changes in the Na emission distribution have  
 78 been attributed to variations in the solar wind IMF and solar transient events (Mangano  
 79 et al., 2013, 2015; Orsini et al., 2018; Milillo et al., 2021). Jasinski et al. (2020) deter-  
 80 mined that a large meteoroid impact event was responsible behind the FIPS observa-  
 81 tion of a sudden ( $< 10$  minute) enhancement of the  $\text{Na}^+$ -group ion flux ( $\sim 10^4 \text{ cm}^{-2} \text{ s}^{-1}$   
 82 at  $\sim 5300$  km). Raines et al. (2018) reported an enhancement of the  $\text{He}^+$  density (up to  
 83  $0.1 \text{ cm}^{-3}$ ) in the northern cusp following the transit of a CME at Mercury.

84 There have been a number of intense solar flare events in modern time. Notewor-  
 85 thy examples include the Bastille Day event on 14 July 2000 (Aulanier et al., 2000), the  
 86 Halloween solar storms in 2003 (Tsurutani et al., 2005) and more recently, a set of strong  
 87 X-class flares in September 2017 (Yan et al., 2018). On Earth, extreme solar flares can  
 88 give rise to solar radiation storms, which can have severe biological effects and disrupt  
 89 satellite operations, and radio blackouts, which affects positioning and satellite naviga-  
 90 tion (National Oceanic and Atmospheric Administration, 2011). Solar flares have also  
 91 been shown to enhance X-ray emission at Jupiter (Maurellis et al., 2000), Saturn (Bhardwaj  
 92 et al., 2005) and disturb Mars’s ionosphere (Mendillo et al., 2006; Fallows et al., 2015).  
 93 To our knowledge, the impact of solar flares on Mercury has not been studied before. Con-  
 94 sidering Mercury’s short heliocentric distance and the unique composition of heavy species  
 95 in Mercury’s exosphere, it is a particularly interesting case to consider.

96 We have developed a model to simulate the impact of a strong X-class solar flare  
 97 on the ion density distribution of  $\text{Mg}^+$ ,  $\text{Na}^+$ ,  $\text{O}^+$  and  $\text{He}^+$  in Mercury’s magnetosphere.  
 98 The solar flare event and the model are described in Section 2. We describe the key re-  
 99 sults in Section 3 and discuss their implications in Section 4. Finally, we summarize our  
 100 findings in Section 5.

## 101 2 Model and Method

### 102 2.1 The X9.3-class Solar Flare on 6 September 2017

103 Between 4-10 September 2017 the active region (AR) 12673 on the Sun released  
 104 a series of solar flares and CMEs that impacted Earth and the planet Mars. Two spe-  
 105 cial issues in the Space Weather journal (Knipp, D., 2018) and the Geophysical Research  
 106 Letters (Diftenbaugh, N., 2018) review the observations that were made from these events  
 107 and the impact they had on the two planets.

108 The strongest solar flare of this period (and solar cycle 24) started at 11:53 Uni-  
 109 versal Time (UT) on 6 September 2017 and reached peak emission at 12:02 UT. The flare  
 110 was detected by the Geostationary Operational Environmental Satellites (GOES) and  
 111 ranked as the 14<sup>th</sup> most intense solar flare observed since measurements began in 1975  
 112 (Berdermann et al., 2018). Solar flares are classified by their maximum energy output,  
 113 which is estimated from measurements in the wavelength range  $\lambda = 0.1 - 0.8 \text{ nm}$  by GOES  
 114 X-ray sensor (XRS). The 6 September flare had a peak energy output of  $9.3 \times 10^{-4} \text{ W/m}^2$   
 115 and was therefore classified as an X9.3-class event. The strongest solar flare detected to  
 116 date occurred on 4 November 2003 and was estimated to X28, which makes it at least  
 117 three times stronger than the 6 September 2017 flare.

118 A flare of similar strength (X8.2) erupted on 10 September 2017 from the same ac-  
 119 tive region and hit the planet Mars. Spacecraft observations of Mars’s upper atmosphere  
 120 after the flare showed signs of heating and expansion of the upper atmosphere (Jain et  
 121 al., 2018), which caused the exosphere and ion density at a given altitude to increase (Elrod  
 122 et al., 2018; Thiemann et al., 2018). The photochemical escape of O was also shown to  
 123 be enhanced as a result of the flare (Thiemann et al., 2018). The 6 and 10 September  
 124 2017 flares likely also affected Mercury but there were no spacecraft in orbit around Mer-  
 125 cury that could study its effects.

## 126 2.2 The Flare Irradiance Spectral Model-Version 2

127 The Flare Irradiance Spectral Model-Version 2 (FISM2; Chamberlin et al., 2020)  
 128 is an empirical model of the solar spectral irradiance. The solar spectral irradiance is es-  
 129 timated at a heliocentric distance of 1 AU in the wavelength range 0.05 to 189.95 nm  
 130 with a spectral cadence of 0.1 nm. FISM2 uses data from the X-Ray Photometer Sys-  
 131 tem (XPS) on the Solar Radiation and Climate Experiment (SORCE) in the wavelength  
 132 range 0-6 nm, the EUV Variability Experiment (EVE) on Solar Dynamics Observatory  
 133 (SDO) between 6-105 nm and the Solar Stellar Irradiance Comparison Experiment (SOL-  
 134 STICE; also on SORCE) between 115-190 nm. The FISM2 output is given in a “daily”  
 135 and “flare” version. The daily output contains the daily average of the solar spectrum  
 136 for any given day since 1947 until the present. The flare product consists of a modeled  
 137 spectrum for every 60 s of the selected day (from 2003 until the present). The FISM2  
 138 solar irradiance spectra are available at <http://lasp.colorado.edu/lisird/data/fism>.

139 The FISM2 model relies on a set of proxies to represent the irradiance variability  
 140 in the full wavelength range (0-190 nm) caused by the solar cycle, solar rotation and so-  
 141 lar flares. The solar spectral irradiance variability due to solar flares is estimated using  
 142 two separate proxies. Measurements from the GOES/XRS B-channel (0.1-0.8 nm) are  
 143 used to model the gradual (thermal) phase of the solar flare (Priest, 1981). The time-  
 144 derivative of the GOES/XRS-B measurements are used to represent the impulsive (non-  
 145 thermal) phase (Neupert, 1968). Only the irradiance variation due to the solar cycle and  
 146 solar rotation is accounted for in the daily product, while the flare product also accounts  
 147 for the irradiance variation due to real solar flare events.

148 We use the FISM2 flare output on 6 September 2017 in order to estimate the time-  
 149 evolution of the photoionization flux for different species during the specified flare event.  
 150 The FISM2 model has been used in the past to study the 6 and 10 September 2017 X-  
 151 class flares (Chamberlin et al., 2018). To calculate the Mg, Na, O and He photoioniza-  
 152 tion frequencies we merge the FISM2 spectra (0-190 nm) with the solar flux model from  
 153 Killen et al. (2009) between 190-1300 nm and use the theoretical photoionization cross  
 154 sections from Verner et al. (1996).

## 155 2.3 The Latmos Ionized Exosphere Model

156 The Latmos IoniZed Exosphere (LIZE) model is a test-particle model which de-  
 157 scribes the 3-D ion density distribution of photo-ions derived from Mercury’s exosphere.  
 158 The model is coupled to a Monte Carlo model of the exosphere (EGM; Leblanc & John-  
 159 son, 2010; Leblanc et al., 2017) and a hybrid model of the magnetosphere (LatHyS; Mod-  
 160 olo et al., 2016, 2018). We make a separate LIZE simulation for each ion species ( $\text{Mg}^+$ ,  
 161  $\text{O}^+$  and  $\text{He}^+$ ). For the O and He exospheres, we used the results of EGM described in  
 162 Werner et al. (2022), whereas for the Mg exosphere those described in Chaufray et al.  
 163 (2021a, 2021b). The EGM model of the Na exosphere has been described previously in  
 164 Leblanc and Johnson (2010) and the He exosphere in Leblanc and Chaufray (2011). We  
 165 find that the 6 September 2017 flare did not cause the Na surface ejection rate by photo-  
 166 stimulated desorption to increase or Mercury’s surface temperature to rise (which con-  
 167 trols the rate of thermal desorption). Surface ejection by ion sputtering or micro-meteoroid

168 vaporization are not affected by the solar radiation conditions. Therefore we make the  
 169 assumption that the neutral Mg, O and He exosphere density does not change signifi-  
 170 cantly during the flare. We use the EGM output at true anomaly angle  $TAA = 180^\circ$   
 171 (i.e. at aphelion) for all species. For the simulation of the magnetosphere, we use the same  
 172 set of solar wind and IMF boundary conditions as “case a” described in Aizawa et al.  
 173 (2021). The LIZE model has been used previously to determine the average ion density  
 174 and phasespace density distribution of  $\text{Na}^+$ ,  $\text{O}^+$  and  $\text{He}^+$  inside Mercury’s magnetosphere  
 175 (Werner et al., 2022). The model gives a similar average density and spatial distribu-  
 176 tion as the  $\text{Na}^+$ -group,  $\text{O}^+$ -group and  $\text{He}^+$  ion density observations made by MESSEN-  
 177 GER/FIPS (Raines et al., 2013).

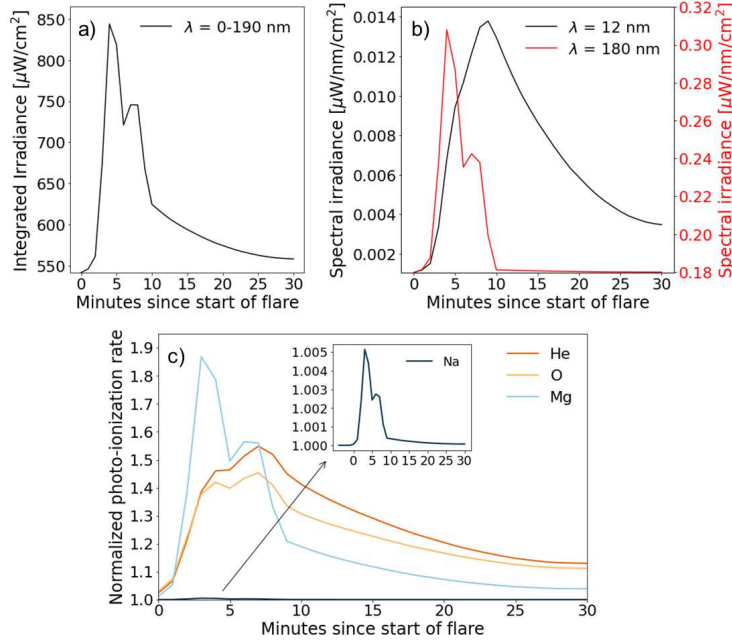
178 For the purpose of this study, we have implemented the capability to use time-dependent  
 179 input conditions with the LIZE model. We make repeated test-particle injections in the  
 180 whole simulation volume with a test-particle weight that depends on the nominal 3-D  
 181 ion production rate and the time-dependent photoionization frequency calculated with  
 182 the FISM2 model. We use a 4-D grid  $(r, \phi, \theta, E)$  where  $r$  is the distance from the planet,  
 183  $\theta$  is the co-latitude,  $\phi$  is the longitude and  $E$  is the kinetic energy. The grid is centered  
 184 on the planet and the simulation volume is bounded between  $r = 1.0 - 3.5$  Mercury  
 185 radii ( $R_M$ ),  $\theta = 0 - \pi$  rad and  $\phi = 0 - 2\pi$  rad. The grid is divided into 65 exponen-  
 186 tially distributed cells along  $r$  ( $\Delta r = 5 - 600$  km), 40 cells along  $\theta$  ( $\Delta\theta = 0.08$  rad)  
 187 and 60 cells along  $\phi$  ( $\Delta\phi = 0.1$  rad). The energy range is  $E = 1 - 10^5$  eV and the en-  
 188 ergy resolution is described by the formula  $(E_i - E_{i-1})/E_i = 0.1$  where  $E_i$  is the  $i$ th  
 189 energy step. All test-particles inside the simulation are synchronously advanced in space  
 190 after every time step ( $dt = 0.01$  s). Every 60 s we inject 50 test-particles with zero ini-  
 191 tial velocity from random positions within each cell on the grid that has a non-zero ion  
 192 production rate (as defined in the corresponding EGM simulation). The output consists  
 193 of “snapshots” of the 3-D ion density distribution. Before triggering the solar flare we  
 194 initialize the simulation volume with 30 minutes of test-particle injections with weights  
 195 which correspond to the nominal photoionization frequency (for each species) in order  
 196 to have a steady state situation of the magnetospheric environment. After this time, the  
 197 deviation between snapshots taken 60 s apart is less than 10%.

### 198 3 Results

#### 199 3.1 Time-evolution of the Mg, Na, O and He photoionization frequency

200 Figure 1a shows the integrated solar spectral irradiance during the first 30 min-  
 201 utes of the 6 September 2017 flare event. To make this particular plot we have used the  
 202 wavelength range 0-190 nm as opposed to the whole wavelength range (0-1300 nm), to  
 203 more clearly show the peaks of the impulsive ( $t = 3$  min) and gradual ( $t = 6 - 7$  min)  
 204 phases of the flare. The flare emission that occurs during the impulsive phase is believed  
 205 to be due to non-thermal acceleration of high speed electrons and protons inside mag-  
 206 netic loops in the solar atmosphere, while the gradual phase is dominated by thermal  
 207 radiation or bremsstrahlung from the hot gas nested inside the magnetic loops (Dennis  
 208 & Schwartz, 1989). Figure 1b shows the solar spectral irradiance at two discrete wave-  
 209 lengths:  $\lambda = 12$  nm and  $\lambda = 180$  nm. The spectral irradiance at  $\lambda = 12$  nm is domi-  
 210 nated by the gradual phase while the relatively cool, impulsive phase typically dominates  
 211 at longer wavelengths. Figure 1c shows the time evolution of the photoionization frequency  
 212 for He, O, Mg and Na normalized to their values before the start of the flare.

213 Na has the highest nominal photoionization frequency of the four species ( $5.0 \times$   
 214  $10^{-6} \text{ s}^{-1}$ ), but the solar flare has a negligible effect on Na (see the inset plot in Figure  
 215 1c). The Mg photoionization frequency is an order of magnitude smaller compared to  
 216 Na ( $4.5 \times 10^{-7} \text{ s}^{-1}$ ) but increases with up to 87% as a result of the flare. The He and  
 217 O photoionization frequencies have a similar time-evolution during the flare (see Figure  
 218 1c) but have different magnitude (He:  $7.5 \times 10^{-8} \text{ s}^{-1}$ ; O:  $3.1 \times 10^{-7} \text{ s}^{-1}$ ). The He den-



**Figure 1.** The (a) integrated solar irradiance during the first 30 minutes of the 6 September 2017 flare in the wavelength interval  $\lambda = 0 - 190$  nm calculated using the FISM2 model, (b) the spectral solar irradiance at the wavelengths  $\lambda = 12$  nm and  $\lambda = 80$  nm and (c) the normalized photoionization frequency for Na, He, O and Mg.

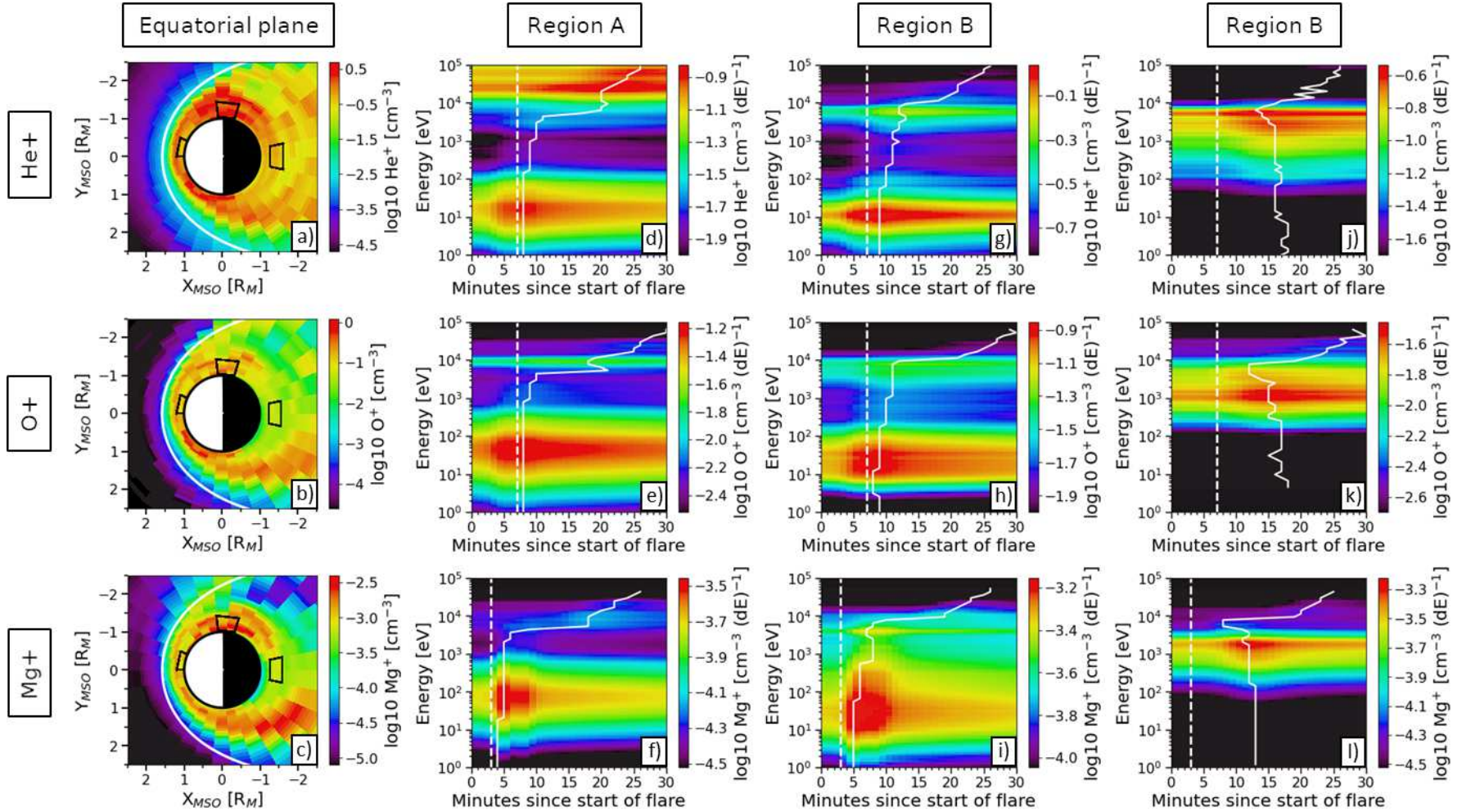
219 sity from the EGM, which is used as input to the LIZE model, is much higher and have  
 220 a larger scale height compared to the O density (Werner et al., 2022). The Mg photoion-  
 221 ization frequency is highest after 3 minutes, while the maximum He and O photoioniza-  
 222 tion frequencies occurs 7 minutes after the start of the flare. This implies that the impu-  
 223 sive flare phase is most effective in raising the Mg photoionization frequency while  
 224 the gradual phase is more important for He and O. The different time-evolution of the  
 225 photoionization frequency for each species and their distribution in the exosphere have  
 226 the potential to create large differences between their ion counterparts in the magneto-  
 227 sphere.

## 228 3.2 Time-evolution of the ion density separated by energy

### 229 3.2.1 The ion energy spectrum before the flare

230 Figure 2a–c show the average  $\text{He}^+$ ,  $\text{O}^+$  and  $\text{Mg}^+$  ion density in the latitude range  
 231  $\pm 30^\circ$  centered on the geometric equatorial plane. We study the evolution of the  $\text{He}^+$ ,  
 232  $\text{O}^+$  and  $\text{Mg}^+$  ion density as a function of time and energy (Figure 2d-l) inside three dif-  
 233 ferent regions in the magnetosphere (black boxes in 2a-2c). The energy spectra in Fig-  
 234 ure 2d-l shows the ion density separated per energy bin and has the unit  $\text{cm}^{-3} \cdot dE^{-1}$ ,  
 235 where the energy bin width  $dE$  is given by  $dE = 0.1E_i$  and  $E_0 = 1$  eV. The first re-  
 236 gion (i.e. Region A) is located near the surface (Altitude: 0-500 km) on the dayside (Lo-  
 237 cal time: 10:30-12:00 h). Region B is located at higher altitudes (Altitude: 100-1100 km)  
 238 near the dawn terminator (Local time: 05:00-06:30 h), and Region C is located near mid-  
 239 night in the nightside plasma sheet (Altitude: 700-1500 km; Local time: 23:00-01:00 h).  
 240 Figure 2d–l show the ion energy distributions (energy spectra) for  $\text{He}^+$ ,  $\text{O}^+$  and  $\text{Mg}^+$   
 241 in Region A-C as a function of time.





**Figure 2.** The (a) He<sup>+</sup> ( $t = 8$  min), (b) O<sup>+</sup> ( $t = 8$  min) and (c) Mg<sup>+</sup> ( $t = 5$  min) ion density in the equatorial plane (average over latitude range  $\pm 30^\circ$ ) and (d - l) the time-evolution of the energy spectra in Region A - C separated by species. In Figure a - c,  $X_{MSO}$  points toward the Sun and  $Y_{MSO}$  points toward dusk. The solid white hyperbolas in panels a - c show the location of the magnetopause boundary, which has been calculated and corrected for the solar wind ram pressure of our simulation ( $P_{ram} = 8$  nPa) following the scheme described in Winslow et al. (2013). The black boxes show the location of Region A - C. The dashed white lines in Figure d - l highlights the time when the photoionization frequency for each species reaches its maximum value. The solid white curves identifies the time when the ion density is highest in each energy channel.



242 Before the flare ( $t = 0$ ), the energy spectra in Region A-B exhibits two distinc-  
 243 tive peaks (Population 1 and 2). Population 1 consists of low-energy ions ( $E = 0 - 100$   
 244 eV) while Population 2 contains much hotter ions ( $E > 10$  keV). The low energy of the  
 245 ions in Population 1 indicate that they have recently been photo-ionized and were likely  
 246 created inside or near Region A-B. On the contrary, Population 2 must either contain  
 247 ions which have been created elsewhere and/or have experienced a different dynamical  
 248 evolution compared to the ions in Population 1 (see Section 4 for an in-depth discussion).  
 249 For  $\text{He}^+$  in Region A, Population 1 has a maximum at  $E = 20$  eV and Population 2  
 250 at  $E = 20$  keV. The energy spectra for  $\text{O}^+$  and  $\text{Mg}^+$  in Region A (see Figure 2e-2f)  
 251 also consists of two ion populations. Population 1 (2) has a mean energy of  $E = 40$  eV  
 252 ( $E = 10$  keV) for  $\text{O}^+$  and  $E = 80$  eV ( $E = 8$  keV) for  $\text{Mg}^+$ . The density of the Pop-  
 253 ulation 1 and 2  $\text{He}^+$  ions in Region A are quite similar, with Population 1 being just  $\sim 40\%$   
 254 more abundant than Population 2. However, for  $\text{O}^+$  and  $\text{Mg}^+$  Population 1 completely  
 255 dominates the energy spectrum and Population 2 only accounts for  $\sim 10\%$  of the total  
 256 ion density. The mean energy of the two ion populations are generally lower in Region  
 257 B: Population 1 (2) has a mean energy of  $E = 10$  eV ( $E = 5$  keV) for  $\text{He}^+$ ,  $E = 30$   
 258 eV ( $E = 8$  keV) for  $\text{O}^+$  and  $E = 30$  eV ( $E = 4$  keV) for  $\text{Mg}^+$ . Region C appears to  
 259 be populated by a single ion population with a relatively high average energy of  $E =$   
 260  $5$  keV for  $\text{He}^+$ ,  $E = 1$  keV for  $\text{O}^+$  and  $E = 2$  keV for  $\text{Mg}^+$ .

### 261 3.2.2 Time-evolution of the ion energy spectrum

262 The difference between the dashed line and the solid curves in Figure 2d - 2l illus-  
 263 trates the time delay between the maximum photoionization frequency and the maxi-  
 264 mum ion density in each energy channel. The time delay for Population 1 in Region A  
 265 is  $\Delta t = 1-2$  minutes for all modeled species. The time delay for Population 2 is longer,  
 266 approximately  $\Delta t = 14-15$  minutes. Similar values are found in Region B. Inside re-  
 267 gion C the maximum ion density occurs at  $t = 14 - 15$  minutes for  $\text{He}^+$ ,  $\text{O}^+$  and at  
 268  $t = 11$  minutes for  $\text{Mg}^+$ . If we compare the dashed and the solid curves in Figure 2j  
 269 - l we find that the time delay is  $\Delta t = 7 - 8$  minutes irrespective of the species.

270 Population 1 typically dominates the total ion density in both Region A and B dur-  
 271 ing the entire simulation for all modeled species. However, the  $\text{He}^+$  Population 1 ( $E =$   
 272  $0-100$  eV) in Region A varies between being twice as dense as Population 2 ( $E > 10$   
 273 keV) at  $t = 8$  minutes, to only 20% more abundant compared to Population 2 at  $t =$   
 274  $22$  minutes. In effect, this causes the average  $\text{He}^+$  density to decay more slowly in Re-  
 275 gion A. The average  $\text{He}^+$  density is elevated by  $\sim 25\%$  compared to the background value  
 276 for almost 10 minutes shortly after the main peak ( $t = 8$  min). This is not the case for  
 277  $\text{O}^+$  and  $\text{Mg}^+$ , that do not possess such a large population of high-energy ions in this re-  
 278 gion.

## 279 4 Discussion

280 The photoionization frequency for different neutral species reach their maximum  
 281 value at different times during a flare. This depends on the photoionization energy thresh-  
 282 old and in particular on the wavelength-dependence of the photoionization cross-section  
 283 for each species. This may cause the impulsive or the gradual flare phase to be the most  
 284 effective in raising the overall photoionization frequency. The time-evolution of the Mg  
 285 (and Na) photoionization frequency exhibit a strong correlation with the impulsive phase  
 286 of the 6 September 2017 flare (see Figure 1c) while the He and O photoionization fre-  
 287 quencies reach their maximum values during the gradual flare phase. This result implies  
 288 that a spacecraft (which carries a plasma mass spectrometer) in orbit around Mercury  
 289 during a strong X-class flare event will first detect an increase of the  $\text{Mg}^+$  density fol-  
 290 lowed by  $\text{He}^+$  and  $\text{O}^+$  several minutes later, regardless of where the spacecraft is located  
 291 inside the magnetosphere. Calculations show that most species that have been observed

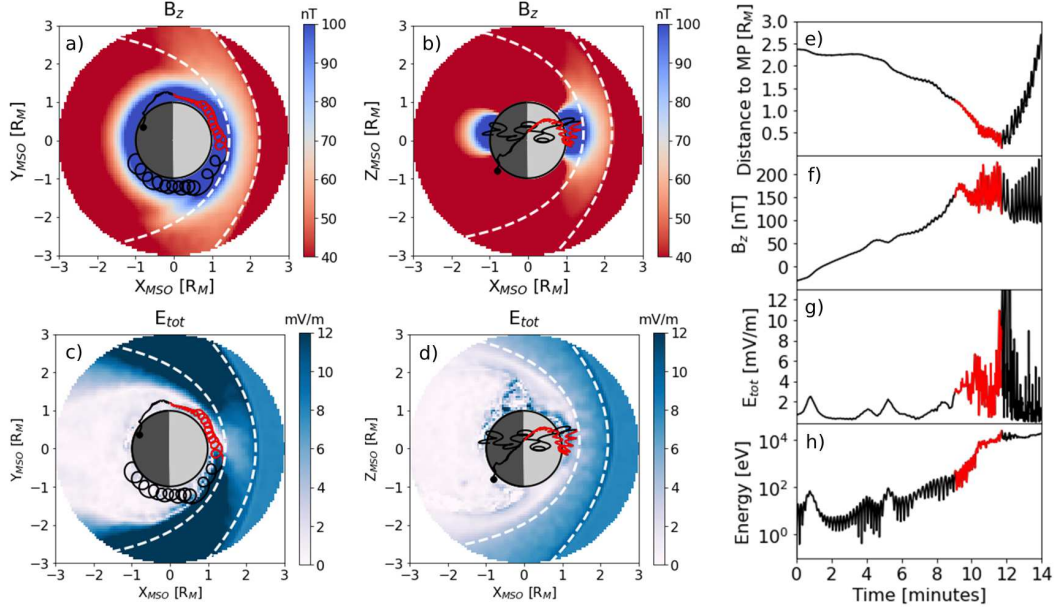
in Mercury’s exosphere (Bida et al., 2000; Bida & Killen, 2017; Broadfoot et al., 1974; McClintock et al., 2008; Potter & Morgan, 1985, 1986; Vervack et al., 2016) or are expected based on observations of Mercury’s surface composition (Evans et al., 2012, 2015; Nittler et al., 2011; Peplowski et al., 2012, 2015) are most affected by the impulsive phase of the 6 September 2017 flare (i.e. H, C, Na, Mg, Al, Si, S, Ar, Ca, Fe). The strength of the impulsive and gradual phase vary on an event-to-event basis. The impulsive flare phase tends to be the dominant phase for small flares, while strong flares like the 6 September 2017 flare often exhibit a relatively strong gradual phase which can last for over an hour (Dennis & Schwartz, 1989).

At most, there are  $2.4 \times 10^{26}$  ( $\text{He}^+$ : 43% increase),  $4.5 \times 10^{25}$  ( $\text{O}^+$ : 38% increase)  $5 \times 10^{23}$  ( $\text{Mg}^+$ : 49% increase) additional  $\text{He}^+$ ,  $\text{O}^+$  and  $\text{Mg}^+$  ions being produced respectively in and outside Mercury’s magnetosphere. The maximum  $\text{He}^+$ ,  $\text{O}^+$  and  $\text{Mg}^+$  ion production during the flare is equal to barely 0.1% of the plasma mass density of the  $\text{Na}^+$  ion population however, and therefore does not cause any significant mass loading of Mercury’s magnetosphere.

Analysis of test-particle trajectories for Population 2 ions reveal that they experience a different dynamical evolution compared to Population 1. Population 2 largely consists of ions which have become quasi-trapped in the closed field line region near Mercury’s magnetic equator. Figure 3 shows an example  $\text{Mg}^+$  test-particle trajectory from the LIZE model which is typical to Population 2. The  $\text{Mg}^+$  test-particle is ejected in the southern hemisphere and travels toward the dayside equatorial region (see Figure 3a-d and f). As the test-particle moves into the dayside hemisphere it approaches the magnetopause (see Figure 3e), and encounters the strong electric field near the magnetosheath (see the red part of the trajectory in Figure 3a-d and g). This causes the ion energy to increase from a few hundred eV to  $> 10$  keV (see Figure 3h) and the test-particle starts to drift around the planet toward the nightside, where it eventually impacts the planet. The small size of Mercury’s magnetosphere prevents the formation of a steady ion drift belt. Low-mass ions like  $\text{He}^+$  can make 1-2 complete orbits before impacting the planet or escaping, while heavier ions like  $\text{Mg}^+$  are typically not able to pass the dayside magnetosphere because of their large gyro radii.

The test-particle trajectory in Figure 3 seems to suggest that the Population 2 ions in Region A does not belong to the Type 0 or Type 1 ion populations described in Glass et al. (2021), but could be part of Type 3. Glass et al. (2021) identified different types of  $\text{Na}^+$  test-particle trajectories which could be responsible for the population of  $> 1$  keV  $\text{Na}^+$  ions observed in Mercury’s northern magnetospheric cusp by FIPS (Raines et al., 2014). Type 0 ions pass through the magnetosheath before crossing the northern cusp, while Type 1 ions move directly into the northern cusp without passing through or coming near the magnetosheath boundary. Any ion which exceeded a distance of  $2 R_M$  from the planet before passing through the cusp was categorized as Type 2, based on the relatively coarse grid resolution of the simulation beyond  $2 R_M$ . Type 3 consists of  $\text{Na}^+$  ions which comes close to the magnetopause but do not cross into the magnetosheath before passing through the northern cusp. The  $\text{Mg}^+$  ion in Figure 3 is energized to  $> 10$  keV before its closest approach to the magnetopause (see Figure 3e and h). It is possible that Type 3 ions are rare at high latitudes simply because they are easily (quasi-)trapped in the closed field line region near the equator and therefore remain at mid-latitudes.

The magnetopause is located farther away from the surface at the dawn terminator compared to the subsolar point due to solar wind aberration. This implies that the solar wind convective electric field have less influence over the ions in Region B compared to Region A, which leads to overall lower ion energies in this region. Region C is located in Mercury’s shadow, where there is no local ion production and ions can only be transported here from elsewhere in the magnetosphere. This explains the lack of a low-energy ion population in Region C and the time delay between the peak ion density in Region



**Figure 3.** Example test-particle trajectory of a  $\text{Mg}^+$  ion from the LIZE model in the (a,c) MSO XY-plane and the (b,d) XZ-plane. Also shown is the magnetic field component  $B_z$  (a,b) and the total electric field  $E_{tot}$  (c,d) from the LathyS simulation. (e) shows the distance of the  $\text{Mg}^+$  ion from the planet, (f) the time-evolution of  $B_z$  experienced by the  $\text{Mg}^+$  ion, (g) the total electric field and (h) the ion energy. The part of the test-particle trajectory highlighted in red indicates a short time period when the ion energy increases from  $\sim 100$  eV to  $>10$  keV. The white dashed curves in (a-d) show the approximate location of the magnetopause and bow shock calculated from Winslow et al. (2013).

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A and Region C. The ions in Region C are mainly sourced by magnetospheric convection from the dayside and the quasi-trapped ion drift belt.

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The two peaks in the solar irradiance from the 6 September flare are relatively pronounced compared to the X8.2-class flare on the 10 September. This is caused by the difference in the optical thickness of the flare emission during the impulsive and gradual phase. The 6 September flare occurred when the active region was located near the center of the solar disk (S09W34) as seen from Earth, while the 10 September flare occurred when the active region was located near the solar limb (S08W88). The emission during the gradual phase of the flare is optically thick and more easily absorbed by the Sun's atmosphere than the impulsive emission which is optically thin. Because the optical path between an observer and the apparent solar limb is longer compared to the center of the solar disk, the intensity of the gradual flare phase emission may change considerably depending on the location of the flare source region. This means that for species like  $\text{He}^+$  and  $\text{O}^+$  the time of the peak photoionization frequency will also change. The  $\text{Mg}^+$  photoionization frequency is mainly controlled by the impulsive flare phase and is therefore less sensitive to the location of the flare source region. It should be noted that the FISM2 flare model is based on GOES observations made at Earth, and will not reflect the true flare radiation profile at Mercury if the planet is located far away from the Sun-Earth line. The 6 September 2017 flare, for instance, erupted closer to the apparent center of the solar disk as seen from Mercury and may have caused the gradual phase flare emission to be even stronger than suggested here.

## 5 Conclusions

We have used a test-particle model of the planetary ion density distribution in Mercury's magnetosphere which accepts time-dependent input conditions. We use this time-dependent capability to model the impact of a real flare event (the X9.3-class flare on 6 September 2017) on different planetary ion species. We find the following:

- The photoionization frequency of Na was not significantly affected, while the photoionization frequencies of Mg, O and He were increased with up to 40 – 80%.
- The maximum He and O photoionization frequencies are delayed by  $\sim 4$  minutes after the maximum Mg photoionization frequency. This is because the photoionization process for these species are mostly affected by the emission released during the gradual flare phase. Consequently, the photoionization frequency of Mg displays a relatively quick decay after the main peak compared to O and He.
- In the dayside magnetosphere, the low-energy ion population experiences a quicker evolution than the high-energy ions. At low altitudes on the dayside,  $\sim 20$  keV energy ions take up to 14 minutes to show a flare enhancement. This comes to show that the planetary ion population experiences different dynamical evolution which have different characteristic timescales.
- In the nightside plasma sheet, there is no local ion production and ions can only be transported here from elsewhere in the magnetosphere. For this reason there is no low-energy ion population in this region. There is a time delay between the maximum ion density on the dayside and the maximum ion density in the nightside of  $\sim 7 - 8$  minutes for all species.

This study shows that predicting the response of Mercury's magnetosphere to a strong solar flare is an intricate problem. What a mass spectrum analyzer on a spacecraft inside Mercury's magnetosphere will measure depends on a number of factors: the species, the location of the flare on the solar disk, the location of the spacecraft and the energy range of the instrument.

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**Figure 1.**



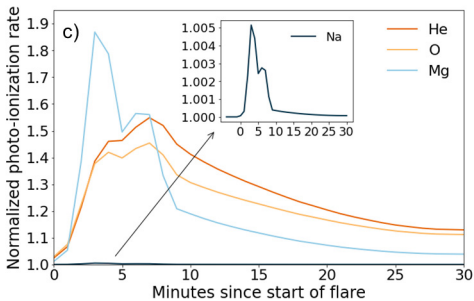
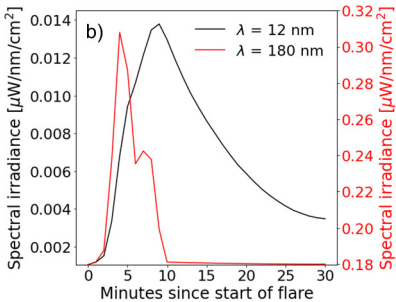
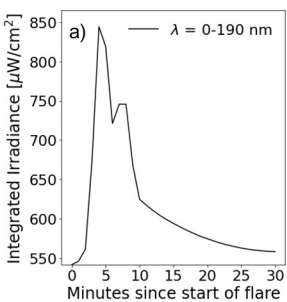


Figure 3.

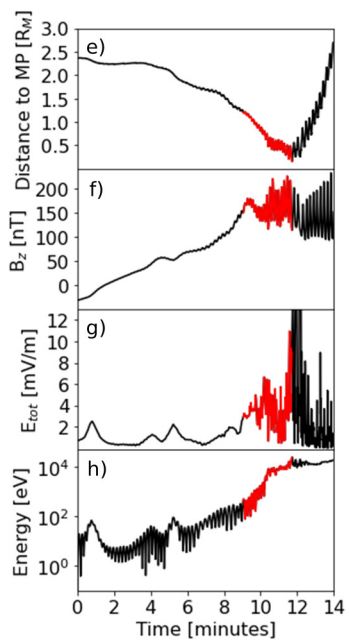
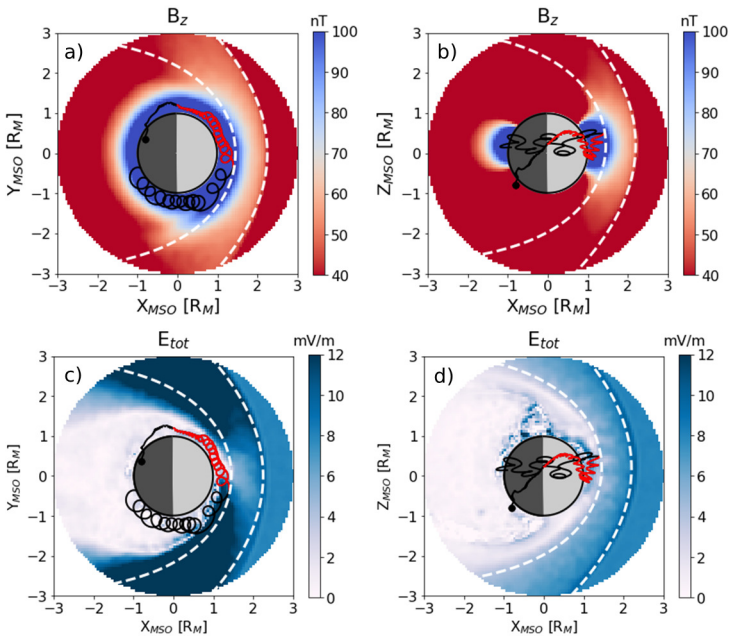


Figure 2.



