Interaction of Space Weather Phenomena with Mars Plasma Environment During Solar Minimum 23/24

Abstract We study the interaction of three solar wind (SW) structures, two stream interaction regions, and one interplanetary coronal mass ejection, with Mars’ plasma environment during November 20–27, 2007. This period corresponds to the solar minimum between the solar cycles 23 and 24 which was characterized by very low values of the SW density and dynamic pressure and low interplanetary magnetic field magnitude. During that time the Mars Express orbit was in the terminator plane, while the Earth, Sun, and Mars were almost aligned, so we use the Advance Composition Explorer and Solar Terrestrial Relations Observatory probes as SW monitors in order to identify and characterize the structures that later hit Mars. We find that the passage of these structures caused strong variations in the bow shock location (between 2.2 and 3.0 \( R_M \)), compression of the magnetospheric cavity (up to 45%), and an increased transterminator flow below 2 \( R_M \) (by a factor of \( \leq 8 \)). This study shows that during times of low solar activity, modest space weather phenomena may cause large variations of plasma flow at Mars.

Plain Language Summary Unlike Earth, Mars does not possess a global magnetic field. Instead it is its ionosphere that represents the obstacle for the solar wind (SW) and thus the induced magnetosphere, magnetosheath, and the bow shock are formed. We make use of the fact that in November 2007, so during the solar minimum 23/24, Mars Express orbit laid in a terminator plane, which made it possible to study transterminator planetary plasma flow. During November 20–27, 2007 Mars interacted with two stream interaction regions and one interplanetary coronal mass ejection. All of these phenomena were of moderate intensity. We know this since at the time Mars and Earth were aligned, so we are able to use Advance Composition Explorer, Solar Terrestrial Relations Observatory (STEREO A), and STEREO B spacecraft as solar monitors. We show that during solar minima moderate SW structures may cause large planetary transterminator flows. These also show variations of their chemistry compositions.

1. Introduction

Mars currently does not possess a global magnetic field and only remnant crustal fields exist on its surface, mostly on the southern hemisphere (Acuña et al., 1998). Due to this, the solar wind (SW) interacts directly with the Martian upper atmosphere and ionosphere, which leads to significant loss of the planet’s atmospheric material.

In the absence of a global magnetosphere, it is the Martian ionosphere which represents an obstacle for the SW and the interplanetary magnetic field (IMF). The super alfvénic and supermagnetosonic SW cannot penetrate into it but it is forced to decelerate and flow around the ionosphere. Part of the deceleration occurs at the bow shock (BS) that stands upstream of Mars and was first detected by Mariner-IV, Mars 2,3,5, and Phobos-2 (Sagdeev & Zakharov, 1989) spacecraft at a subsolar distance of \( \sim 3 \) Martian radii (\( R_M \)).

As the SW slows down, the IMF drapes around and piles up upstream of the ionosphere, forming an induced magnetosphere. The region where the IMF piles up is called the magnetic pileup region (MPR) and is delimited by a magnetic pileup boundary (MPB). Inside the MPR the magnetic field rotates, its magnitude...
increases, fluctuations are reduced, and energetic particle fluxes diminish. The volume of space delimited by the MPB is also called the magnetospheric cavity (Dubinin et al., 2009).

The region between the MPB and the BS is called the magnetosheath and is characterized by turbulent B-fields and energized electrons (Acuña et al., 1998). The planet’s ionosphere, MPR, and the magnetosheath form what is known as near-Mars plasma environment.

Normally the hot magnetosheath plasma and the planet’s ionospheric plasma do not mix. They are separated by boundaries that were defined based on observational data. The ionopause was first inferred from radio occultation measurements (Kliore, 1992) and confirmed by Acuña et al. (1998). It is located at altitudes as low as 200–300 km (see also Duru et al., 2009; Vogt et al., 2015) and corresponds to the region where energetic (E > 50 eV) electron fluxes drop by an order of magnitude, while intense cold electron fluxes (E < 10 eV) are observed (Acuña et al., 1998). The photoelectron boundary (PEB, i.e., Mitchell et al., 2001; Lundin et al., 2004; Garnier et al., 2017) separates ionospheric electrons from shocked magnetosheath electrons at higher altitudes. Photoelectrons (energy range 20–50 eV) at Mars are produced due to extreme ultraviolet (EUV) light and X-rays emitted by the Sun. Especially important is the 30.4 nm Helium II spectral line that photoionizes neutral CO₂ and O particles. Finally, due to the lack of magnetometers (MAGs) onboard the Mars Express (MEX, Schmidt, 2003) mission, the induced magnetosphere boundary (IMB) was defined as the region where the SW stops while its interior is dominated by plasma of planetary origin (Lundin et al., 2004).

There are many phenomena that influence the Martian ionosphere/induced magnetosphere system. Among them are the varying EUV and X-ray fluxes during solar cycles and during solar flares (see Figure 1 and Fletcher et al., 2011), varying SW dynamic pressure (P_{dyn,SW}), transient structures such as stream interaction regions (SIRs) including corotating interaction regions (CIRs, i.e., Gosling & Pizzo, 1999) and interplanetary coronal mass ejections (ICMEs, Sheeley et al., 1985), solar energetic particle (SEP, i.e., Reames, 1996; Schwenn, 2006), and energetic storm particle (ESP, Cohen, 2006) events. We briefly describe the effects of some of these events, relevant to the present study, on Mars’ plasma environment.

Figure 1. From top to bottom: (a) monthly averaged sunspot number (SSN), (b) total solar irradiance at Earth (in Wm⁻², red dots) and Mars’ heliocentric distance in astronomical units (A.U., black curve), (c) solar extreme ultraviolet (EUV), and (d) solar X-ray fluxes at Earth (red) and Mars (purple) in mWm⁻² during 2007 – 2018. The vertical green line marks the time of interest of this study.
1.1. Stream Interaction Regions

The interaction of Mars’ plasma environment with SIRs has been studied by Dubinin et al. (2009), Morgan et al. (2010), Oppenorth et al. (2013), Lee et al. (2017), and (2018), and others. Strong perturbations of the Martian magnetosphere and ionosphere during SIR passages were reported together with increased ionospheric electron densities. In some cases, the magnetic barrier ceased to be a shield for the incoming SW, and large amount of SW could penetrate into the magnetosphere sweeping out cold ionospheric plasma. Statistical studies of CIRs on the atmosphere of Mars were performed by Edberg, Nilsson, et al. (2010) and by Nilsson et al. (2011) who reported that ion escape fluxes incremented by a factor of ~2.5 during pressure pulses produced by CIRs.

1.2. SW Dynamic Pressure

Another factor that changes during solar cycle is the SW dynamic pressure $P_{\text{dyn,SW}}$. $P_{\text{dyn,SW}}$ increases may occur, for example, behind interplanetary (IP) shocks, during fast SW streams, or inside SIRs. Harada et al. (2017), for example, studied the response of the Martian ionosphere to a SIR-related IP shock. A sharp increase in the local ionospheric B-field at 478 km at a solar zenith angle (SZA) of 78° was observed, which points toward the compression of the Martian-induced magnetosphere.

The effect of the high $P_{\text{dyn,SW}}$ on the Martian plasma environment was studied by several authors who obtained some contradicting results. Edberg et al. (2009) showed that during high $P_{\text{dyn,SW}}$ the SW can penetrate into the ionosphere and enhance its erosion. Nilsson et al. (2011) also found a correlation between ion escape and the $P_{\text{dyn,SW}}$. Ramstad, Barabash, Futaana, Nilsson, et al. (2017) on the other hand found a weak inverse dependence of the ion escape rate on the $P_{\text{dyn,SW}}$.

1.3. Interplanetary Coronal Mass Ejections

The interaction of Mars’ plasma system with ICMEs has been a topic of several works in the recent past. Most of these works study impacts of large ICMEs, such as the Halloween events (Crider et al., 2005; Espley et al., 2005), the October 14, 2014 (Witasse et al., 2017), the December 5, 2005 (Morgan et al., 2014), March 8, 2015 (Curry et al., 2015; Duru et al., 2017; Jakosky et al., 2015; Y. J. Ma et al., 2017), and September 13, 2017 (Guo, Lillis, et al., 2018; Lee et al., 2018; Ma et al., 2018; Ramstad et al., 2018; Xu et al., 2018; SánchezCano et al., 2019) events.

Large ICMEs are often accompanied by intense SEP/ESP events and solar flares. It is thought that SEP/ESP events augment ion loss at unmagnetized planets through extra charging of the ionosphere (Futaana et al., 2008; Morgan et al., 2014; Oppenorth et al., 2013). SEP particles are able to penetrate the induced magnetic barrier and precipitate into the planetary atmospheres, modifying heating, dissociation, and ionization rates and causing auroral emissions (Ramstad et al., 2018).

The compression of the induced magnetosphere reduces the altitude of the MPB (from the typical value of 800–1,200 km to only 400 km, see Crider et al., 2005) thereby exposing the plasma from the ionosphere and lower exosphere directly to the SW flow. This enables charge exchange between the SW ions and the atmospheric neutrals which leads to further enhancement of the ionospheric ion escape. Ehresmann et al. (2018) studied the effect of energetic particles on Mars’ surface during the September 2017 event. It was found that fluxes of protons with energies below 100 MeV were enhanced by a factor of 30, and those with higher energies by a factor of 4. A completely different result, however, was obtained by Ramstad, Barabash, Futaana, Yamauchi, et al. (2017) who studied an impact of an extremely strong ICME that hit Mars on July 12, 2011. These authors found no significant increase of the ion escape rates during that time.

Numerical simulations of such events (e.g., Curry et al., 2015; Dong et al., 2014; Jakosky et al., 2015; Y. J. Ma et al., 2017; Romanelli et al., 2018) predict planetary ion escape rates increase by a factor of 2–10. Curry et al. (2015) proposed that highest O+ escape rates occur during the passage of the sheath region, which is when the $P_{\text{dyn,SW}}$ is largest.

Other effects of large ICMEs include oscillations of the ionosphere, appearance of ionization at low altitude in the atmosphere (SánchezCano et al., 2019), and extension of the ionospheric peak to up to 115° of
SZA (as opposed to ≤100° during quiet times, Morgan et al., 2014) and variations of all plasma boundaries (Edberg, Lester, et al., 2010; Ma et al., 2018; Trotignon et al., 2006; Romanelli et al., 2018; Xu et al., 2018).

1.4. Small Events during Solar Minima

To our best knowledge there has been only one study that dealt with the interaction between Mars plasma environment and small-scale ICME (lasting only about 5 h) and SIR during solar minimum (Sánchez-Cano et al., 2017).

Sánchez-Cano et al. (2017) studied a Mars plasma system response to two SW disturbances that arrived to Mars within ~1 day on March 7–8, 2008. The first disturbance was a small-scale ICME-like structure and the second a high-speed SW. The structure caused a strong compression of the Martian-induced magnetosphere and ionosphere lasting for ~3 MEX orbits (~20 h). The fast SW stream caused yet another compression of both regions and fragmentation of the ionosphere for several days. It was concluded by the authors that during solar minima, small SW transients may cause large and long-lasting perturbations of Mars’ plasma system.

In this work, we study the impact of SW transients on Martian plasma environment during solar minimum 23/24. Specifically, we perform a case study of impact of an ICME and two SIRs on Mars’ plasma environment starting on November 22, 2007. Although, the properties of these transients were similar to those studied by Sánchez-Cano et al. (2017), there are some important differences between the two events. In our case, MEX orbit lies in the terminator plane. This enables us to directly study ion flow across the terminator plane. Also, in our case the SIRs and the ICME arrive separately so impacts of each transient can be studied separately.

With this study, we aim to contribute to the understanding of what is the impact of relatively small SW transients on Mars’ plasma environment during times of low solar activity. We mainly focus on how the plasma boundaries are affected by these phenomena and how the terminator flow behaves during such perturbed times. Some of the plasma boundaries, such as the MPB, are partially identified without magnetic field measurements. Some boundaries such as PEB, IMB, MPB, and ionopause may lie close together making it difficult to clearly differentiate among them, though overall their presence indicates the crossing from the magnetosheath into the ionospheric environment. Hence in the rest of the text, whenever we observe the spacecraft crossing from the magnetosheath into the ionosphere, we talk about the crossing of the IMB.

2. Instrumentation

During the studied time period, the Sun, Earth, and Mars were aligned in that same order. This enables us to use the two Solar Terrestrial Relations Observatory (STEREO) probes, which were located close to Earth at the time, and the Advance Composition Explorer (ACE) as SW monitors in order to understand better the observations of the MEX mission.

STEREO mission consists of two identical probes in the orbit around the Sun at approximately 1 AU. We use data from several instruments from the In situ Measurements of Particles And CME Transients (IMPACT, Luhmann et al., 2008) suite: (i) MAG(Acuña et al., 2008) that provides accurate measurements of the magnetic field with subsecond time resolution and (ii) Plasma and Suprathermal Ion Composition (PLASTIC, Galvin et al., 2008) that provides ion measurement in the 0.3–80 keV energy range.

ACE mission is located at the Lagrangian L1 point in front of the Earth. Its magnetic field data were obtained by the magnetic field experiment (Smith et al., 1998) and the bulk SW moments were obtained by the Solar Wind Electron Proton Alpha Monitor (SWEPAM, McComas et al., 1998).

For measurements at Mars we use the data from the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3, Barabash et al., 2004; 2006) experiment onboard MEX. ASPERA-3 has several sensors among which are the Electron Spectrometer (ELS) and the Ion Mass Analyzer (IMA). ELS covers the range between 0.01 and 20 keV with a field of view of 4 × 360° (Fränz et al., 2010). IMA consists of an electrostatic deflector which is followed by a top hat electrostatic analyzer, a circular magnetic separator, and finally by a circular microchannel plate (MCP). IMA had several software patches installed throughout time.
These patches allowed for an expansion of the instrument’s energy range in which it operates (e.g., Fränz et al., 2010; Lundin et al., 2008; Nilsson et al., 2010; Rojas-Castillo et al., 2018). In November 2007 the IMA energy range was 0.01–36 keV/q and the energy resolution was 7% with an instantaneous field of view of 4.5°×360°. An elevation scanning of ±45° for energies <50 eV allows IMA to obtain a 3D spectrum at these energies after 192 s when operating in the maximum operational mode.

It should be noticed that for ions below 50 eV there is no elevation scanning and the IMA field of view is therefore limited to 6°×360° (Fränz et al., 2010). This means that the number density of the low energy ions could be underestimated.

For this work we use the IMA plasma data sets that are available through AMDA web tool (http://amda.irap.omp.eu/) and have been processed using similar as that described in Fedorov et al. (2011) for very similar IMA instrument onboard Venus Express in order to reconstruct the ion distributions and the plasma moments. We use IMA measurements for O⁺ and O₂⁺ as they are the main heavy ion species in the Mars environment and are well resolved by the instrument (Rojas-Castillo et al., 2018).

We also use the High-Energy Neutron Detector (HEND) onboard the Mars Odyssey that is composed of two scintillators that provide measurements of charged particles and energetic photons (e.g., Boynton et al., 2004; Sánchez-Cano et al., 2018; Zeitlin et al., 2010). We use the data on particles with energies between ∼195 keV and 1,000 keV (Livshits et al., 2006) provided by the outer scintillator.

3. Observations at 1 AU

3.1. EUV and X-Ray Data

In order to put the observed event in the context of conditions prevailing in the IP space during the time of interest, we show in Figure 1 (a) the monthly smoothed sunspot number (from Sunspot Index and Long-term Solar Observations available at http://www.sidc.be/silso/), (b) the total solar irradiance at Earth (red dots, from SOlar Radiation & Climate Experiment (SORCE), available at http://lasp.colorado.edu/home/sorce/) together with the Mars’ heliocentric distance (black line), (c) the solar EUV flux at 30.5 nm at Earth (red) and Mars (purple), and (d) the solar X-ray flux between 0.1 nm and 7.0 nm at Earth (red) and scaled (as 1/r²) to Mars (purple) between January 1, 2007 and December 31, 2017. The green dashed line on the bottom panel marks the period when the event studied here was observed. It can be seen that the period of interest was characterized by very low EUV and X-ray fluxes compared to the rest of the solar cycle.

3.2. IMF and Plasma Data

Next we use the data from STEREO A (STA), STEREO B (STB), and ACE missions in order to describe the state of the SW and the IMF between November 17 and 24, 2007. During this time period the three spacecraft observed SW structures that later propagated to Mars (see also Table 1).

We can see in Figure 2, obtained from the STEREO Science Center (https://stereo-ssc.nascom.nasa.gov), that STA and Mars were practically aligned, while the difference in heliocentric longitude between STA and...
Earth was ∼20° and that between STA and STB was ∼40°. We can thus conclude that the same structure that hit STA, STB, and ACE also reached Mars at a later time.

A detailed look at the STEREO and ACE data provides a more complete information on the SW transient itself. Figure 3a) shows data from STB. Panels exhibit: (i) IMF magnitude in units of nT, (ii) IMF components (nT) in RTN coordinates (Radial-Tangential-Normal coordinates: X axis points from Sun toward the spacecraft, while the Y axis is the cross product of the solar rotational axis and X, and lies in the solar equatorial plane), (iii) plasma ion density (cm−3), (iv) SW velocity and components (kms−1) in RTN system, (v) temperature (K), and (vi) SW dynamic pressure (P_{dyn}, nPa) at 1 AU (black) and scaled (as 1/r^2) to Mars (red) between November 17 and 24.

We can see that on November 19, a SW structure arrived at STB. Its main signatures are increased B-field, density, and P_{dyn}. During this transit, the SW velocity increases from 300 to 700 kms−1. All this shows that the structure is a SIR (shadowed in red around a green shading). However, smooth rotations of the B-field components on November 20, point to an ICME (shadowed in green) embedded inside the SIR, so the transient is a complex event. Toward the end of November 23, there appears to be another structure in the data, which we classified as another SIR (shadowed in red).

Figure 3b and 3c show ACE and STA data, respectively, in the same format as Figure 3a. We can see that the appearance of the transients changes. At ACE the smooth B-field rotations, indicative of the ICME (green), appear closer to the upstream edge of the first SIR (red), while in STA data the first SIR (red) is preceded by the ICME (green). The reason for such relative timings of the ICME and the SIR is because the top SW speed inside the SIR is larger than inside the ICME. At STB position the SIR had more time to expand outwards and had reached larger heliocentric distances than at STA. Thus, at STB the SIR already overtook the ICME, while at STA it had had barely caught up with it. This implies that we should expect Mars to be reached first by the SIR and later by the ICME. The second, less prominent SIR observed by the STB was also observed by ACE and STA on November 22.

Another SW feature can be observed from the Figures 3a–3c: the SW P_{dyn} (panels vi) at 1 AU just before the arrival of the ICME + SIR structure is very low, about 0.81 nPa. If we scale it to the Mars distance at the time (1.53 A.U.), assuming that it varies with the heliocentric distance as 1/r^2, we get even lower P_{dyn} estimate of 0.35 nPa.

4. Measurements at Mars

4.1. Overview

Figure 4 shows the MEX orbit during 20–27 November 2007. We use the Mars-centered Solar Orbital (MSO) coordinate system in which the x-axis points from Mars to the Sun, the y-axis points antiparallel to Mars’ orbital velocity, while the z-axis completes the right-handed coordinate system. The coordinates are expressed in units of Mars radius (R_{M}). The dotted and dashed lines represent the BS and IMB according to the model by Vignes et al. (2000), and the cyan arrow shows the travel direction of MEX.

We can see that during the period of interest the MEX orbit was in the terminator plane. This enables us to estimate the trans-terminator ion flow much more directly. Its orbital period was 6 h and 43 min. Its periapsis was on the southern hemisphere on the dusk side at the altitude of ∼300 km, while apoapsis occurred at the distance of ∼3 R_{M}.

We first look at the MEX IMA data during November 20–27, 2007 (Figure 5). Panels exhibit: (a) particle energy flux spectra (in units of keV/(cm^2 s ster keV)), (b) plasma number density (cm−3), (c) velocity (kms−1), (d) thermal pressure (nPa), (e) SW dynamic pressure (nPa), and (f) temperature (eV). These data are obtained directly from the ClWeb platform (http://clweb.irap.omp.eu/).
Strong variations of plasma parameters occur during each orbit because MEX enters very different plasma regions (SW, magnetosheath, ionosphere) with very different plasma properties. The largest densities are measured inside the ionosphere, while velocity, temperature, and $P_{\text{dyn,SW}}$ peak when the spacecraft is either in the magnetosheath or in the SW. However, we can see that these parameters also vary from orbit to orbit.

It can be easily seen that three events hit Mars. Their signatures are the increases of ion densities, thermal pressures, and the ion dynamic pressure during times when MEX was in the SW. Increments of the SW velocity are not as clear as in the other parameters. The temperatures are lower during perturbed times than during quiet times. The blue, red, and green lines above the plots indicate quiet, SIR-perturbed, and ICME-perturbed times, respectively. The first event was observed at Mars from November 22, \(\sim 9:30\) UT to November 24 \(\sim 9:00\) UT (orbits #4995–5002). The onset of the second event was on November 24, at \(\sim 22:40\) UT and it was observed until November 25, \(14:30\) UT (#5004–5007). The third event arrived at Mars on November 26, and it was observed only during two orbits (#5009–5010; see also Table 1). These times are approximate since MEX performed observations only during \(\sim 3\) h intervals centered around the times of its closest approach to the planet.

The $P_{\text{dyn,SW}}$ increases strongly during the first SIR (from \(\lesssim 1\) nPa to \(\sim 7\) nPa), which represents a 600% increase. During the second and the third event (the ICME and another SIR, respectively) the $P_{\text{dyn,SW}}$ increases to \(\sim 5.5\) nPa and \(\sim 5\) nPa, respectively, representing a 450% and 400% increases with respect to the quiet times before the arrival of the first structure.

Figure 6 shows fluxes of ions with energies between \(\sim 30\) keV and \(\sim 195\) keV measured by HEND detector onboard the Mars Odyssey. We can see that these fluxes were gradually increasing until early November 22, at which point they decreased abruptly. After that there is one more spike at the beginning of November 23, followed by a drop. We can see from Figure 5b that these dates coincide with the passage of the first SIR. Data in Figure 6 therefore indicate a Forbush decrease of energetic ions. Such decreases are commonly observed at Mars (e.g., Guo, Dumbovi, et al., 2018; Möstl et al., 2015; Witasse et al., 2017). We also examined the behavior of ion fluxes with energies between 195 keV and 1 MeV (not shown) which did not exhibit such variations.

### 4.2. Electron Spectra

Figure 7 shows spectra during the orbit #4997 on November 22, 2007. The colors represent the logarithm of particle flux (in units of \(s^{-1}\) cm\(^{-2}\) sr\(^{-1}\) keV\(^{-1}\)), and the vertical red lines mark the times of plasma boundaries crossings. In the beginning of this time, interval MEX observed hot electron population typical of that in Mars’ magnetosheath. At around 21:10 UT such population becomes gradually colder with its maximum energy decreasing until \(\sim 21:20\) UT, when the spacecraft crosses the IMB. After that only electrons with \(E \lesssim 50\) eV are observed, typical of those in the Martian ionosphere. We call the whole interval when such electrons are observed simultaneously with ion of planetary origin, the ionospheric cavity. Later, at \(\sim 21:50\) UT the spacecraft enters the magnetosheath again and it remains inside it until \(\sim 23:40\) UT when an abrupt change in electron properties occurs. This is the time when MEX crossed the BS and entered into the SW.

Figure 8 exhibits several ELS electron spectra during the period between November 21 and 26. Dates and orbit numbers are provided on each panel. The first panel (orbit #4992) shows electron spectrum on a quiet day before the arrival of the SIRs and ICME.
The data for this orbit start at 10:26 UT on November 21. Relatively cold electron population with energies $\lesssim 30$ eV indicates that the spacecraft was initially in the SW. After $\sim 10:42$ UT the spacecraft observed an onset of intense fluxes (red and green traces) of hot electrons with energies up to $\sim 300$ eV. This is indicative of the Martian BS crossing and the entrance in Mars’ magnetosheath. At $\sim 11:27$ UT the spacecraft crosses the IMB and enters into the ionosphere which is characterized by cold electrons with energies $\lesssim 50$ eV. The spacecraft stays inside the magnetospheric cavity until $\sim 12:20$ UT when it crosses the IMB again and enters the magnetosheath. At $\sim 12:56$ UT the spacecraft crosses the BS again and enters the SW. During its time in the ionosphere MEX detects hot electrons between $\sim 11:50$ and 11:53 UT with energies up to $\sim 400$ eV. We note that during this orbit, both observed plasma boundary (BS, IMB) crossings are well defined and abrupt.

The next panel shows data during the orbit #4997 which is when the first SIR already arrived at Mars (there are no electron data for orbits #4993–4996). The most striking difference with the previous orbit is that the magnetosheath electron fluxes became much more intense, pointing to higher density in the magnetosheath. During its inbound flight MEX did not observe typical signatures of neither the SW nor the BS. This means that the BS moved away from the planet and was either crossed before the beginning of the ELS measurements or that it was located beyond the MEX orbit. The outbound BS crossing is easily identified at $\sim 22:40$ UT. The electron fluxes in the SW are more intense than they were during the orbit #4992. Finally, the time that MEX spends inside the magnetospheric cavity is much shorter ($\sim 22$ min) than before ($\sim 113$ min). Inside it MEX encounters hot magnetosheath-like electron fluxes several times (see also the Figure 7). These encounters may mean that hot magnetosheath plasma temporarily displaced ionospheric plasma at some locations crossed by the spacecraft, similar to what was reported by Sánchez-Cano et al. (2017).

Intense electron fluxes are present throughout the following orbit #4998. The main difference with the previous orbit is that the BS is observed during inbound crossing at $\sim 02:55$ UT and that the spacecraft remains inside the magnetospheric cavity for $\sim 30$ min. Several hot electron fluxes are observed during ionosphere crossing possibly showing that parcels of hot magnetosheath plasma displaced ionospheric plasma at spacecraft altitudes. During the orbits #4999–5001 the electron fluxes diminish and the magnetospheric cavity expands. During the orbit #5002 the plasma configuration resembles that during the orbit #4992. During orbits #5003–5006 the electron fluxes increase again which indicates the compression of the planet’s magnetosheath and induced magnetosphere. This time period coincides with the arrival of the ICME at Mars.

Electron fluxes during the orbit #5003 exhibit several distinct features. The most obvious is that the intensity of the magnetosheath electron flux fluctuates, which is especially true during the outbound crossing. During the inbound portion of the orbit, the electrons in the magnetosheath seem to heat more gradually and their maximum energy also augments gradually from the BS toward the IMB. Once inside the ionosphere, we see intense fluxes of electrons with very low energies between 5 eV and 10 eV. These fluxes are observed also during the outbound crossing from the ionosphere into the magnetosheath. The magnetospheric cavity is

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**Figure 5.** Mars Express Ion Mass Analyzer observations during November 20–27, 2007. Panels show ion (a) PDF spectrogram, (b) ion density, (c) velocity, (d) thermal pressure, (e) dynamic pressure, and (f) temperature. The blue, red, and green lines above the plots indicate quiet, stream interaction region perturbed, and interplanetary coronal mass ejection perturbed times, respectively.

**Figure 6.** Suprathermal particles observed by High-Energy Neutron Detector during November 20–27, 2007.
Figure 7. Electron Spectrometer spectrogram during a portion of the orbit #4997. Purple lines on the bottom mark the times when hot electrons appear inside the ionosphere.

Figure 8. Electron spectrograms for successive orbits between November 21, and November 26, 2007. The dates and Mars Express orbit numbers are provided for each panel.
observed for \( \sim 30 \) min in the data, which is less than during the quiet time orbit #4992, but similar to the duration during the orbit #4998 when the SIR was passing the planet.

The following orbits (#5007–5008) correspond to intervals when Mars' ionosphere/magnetosheath system was recovering. During the orbit #5010 the electron fluxes increase again somewhat, which is a consequence of the arrival of the second, smaller SIR.

### 4.3. Ion Spectra

Figure 9 shows spectra of \( O^+ \) and \( O_2^+ \) ions during the same orbits as shown in Figure 8. We note that the wide trace at highest energies (>500 eV) that appears during the orbit #4997–4998 is mainly due to contamination by magnetosheath protons, although the electrons with \( E > 1 \) MeV and protons with \( E > 20 \) MeV, such as those occurring during SEP/EPS events, may also generate IMA background counts during perturbed times (Ramstad et al., 2018).

The spectra in Figure 9 show some features that were already observed in electron data, namely, that the transition between the magnetosheath and ionosphere is abrupt and well defined during quiet times (orbit #4992) and thus corresponds to the IMB. During perturbed times (orbit #4997–5001, 5003–5006, and 5010) the ionospheric and magnetosheath proton fluxes are enhanced and the ionospheric cavity is reduced. During quiet times the heavy ions exhibit energies below 30 eV, but this changes during perturbed times when we observe accelerated heavy ion fluxes with energies up to \( \sim 350 \) eV.
4.4. Plasma Boundaries

Figure 10 shows the behavior of the plasma boundaries (BS, IMB) during November 20–27, 2007 determined from the electron spectra. Panels (a) and (b) show locations at which the first inbound and the last outbound crossings of the BS and the IMB, respectively, occurred in the $Y_{MEO}-Z_{MEO}$ plane. Blue, red, and green symbols represent crossings during quiet times, SIR-perturbed times and ICME-perturbed times, respectively. The plus signs represent the bow-shock crossing while the asterisks represent the IMB crossings.

Panels (c) and (d) show the distance from the center of Mars at which BS and IMB crossings were observed during inbound and outbound, respectively, parts of the orbits, as a function of MEX orbit number.
We can see that during times when the first SIR was passing the planet the BS location fluctuated most, between 2.2 \( R_M \) (inbound crossing) and \( \sim 3 \ R_M \) (outbound crossing). During the orbit \#4997 the inbound BS crossing was not observed, so the BS was probably located even farther out from the planet.

This means that either the BS was located beyond where MEX began gathering data during this orbit. During the ICME passage and the following quiet time orbits BS and IMB locations fluctuated much less. During the ICME passage the inbound (outbound) crossings occurred at the distance of \( \sim 2.7 \ R_M \) (\( \sim 2.4 \ R_M \)). After the ICME the inbound BS crossings occurred at monotonically diminishing distances between \( \sim 2.7 \ R_M \) and \( \sim 2.2 \ R_M \). The outbound BS crossings occurred at distances that fluctuated between 2.5 \( R_M \) and 2.0 \( R_M \).

The distances at which the IMB was crossed show a more systematic behavior. They tend to be largest during quiet times (between 1.2 and 1.6 \( R_M \) during inbound crossings and 1.1 and 1.7 \( R_M \) during outbound crossings) with the exception of the inbound crossings during the second SIR.

The IMB was observed at smallest distances from the planet during the first SIR and the ICME passage. This shows that the magnetospheric cavity was compressed during these times.

4.5. Plasma Flow

In this section we show how the SIRs and the ICMEs affected the transterminator plasma flow. Due to the limited availability of the data we limit the study of transterminator flow to \( O^+ \) and \( O_2^+ \) ion species and to radial distances below 2 \( R_M \).

Figure 11 shows how the ion density and velocity changed during selected orbits. It exhibits data during six orbits during quiet times (panels a, c, f, and h), during the SIRs passage (panels b, e, g, and j), and during the ICME passage (panels d, and i) in terminator and meridional planes.

The colors along the MEX orbit in Figure 11 represent the logarithm of density in units of \( m^{-3} \), while the arrows represent the projected plasma bulk velocity. The ion densities in the magnetosheath are much lower than in the ionosphere and are mostly represented with purple colors. In the ionosphere they are represented with green, yellow, and red.

We can see that the velocity vectors of \( O^+ \) and \( O_2^+ \) show similar behaviors. They point in approximately the same directions although the \( O^+ \) vectors are longer (higher velocities) than those of \( O_2^+ \).

During the quiet-time orbit \#4992 most velocity vectors of either species have negative \( V_{Y,MSO} \) and positive \( V_{Z,MSO} \) components implying upward and downward movement. The plasma velocities near the apoapsis are very small with negative \( V_{X,MSO} \). The dominant velocity component is the negative \( V_{X,MSO} \).

As the first SIR arrives (orbit \#4998) the velocities do not increase substantially; however, they obtain a negative \( V_{Z,MSO} \) component. Velocities exhibit increased magnitudes during the quiet-time orbit \#5000. During the ICME-perturbed orbit \#5006 the velocity magnitudes decrease. What is interesting is that during the passage of the second SIR (orbit \#5010) the velocities of the ionospheric ions are rather low but those in the magnetosheath are strongly augmented. The magnetosheath velocities exhibit a strong positive \( V_{Z,MSO} \) components which contrast the ionospheric velocities with negative \( V_{Z,MSO} \).

4.5.1. Transterminator Flow

The fact that the MEX orbit is practically in the terminator plane makes it possible to directly estimate the total transterminator flow of different ion species.

For this we first calculate the ion flow density \( j_i \) perpendicular to the terminator plane at a time \( t \), by multiplying the ion velocity along \( X_{MSO} \) with number density at each MEX position. This was done for inbound parts of the orbits and only for distances \( \leq 2 \ R_M \) from the center of the planet:

\[
 j_i = n_i V_{X,MSO} .
\]

The results are shown in Figure 12. \( O^+ \) values are plotted on panel (a) and \( O_2^+ \) values on panel (b). Blue, red, and green traces and symbols denote quiet, SIR-perturbed, and ICME-perturbed times, respectively.
values for the first SIR are presented as pale red traces and symbols so to distinguish them from the values during the passage of the second SIR.

We can see that the behavior of the flow density is similar for both species but that O$^+$ flow densities are higher. This is expected since the O$^+$ is the dominant species at radial distances such as those studied here (e.g., Lundin et al., 2009). During quiet times the flow density diminishes with radial distance almost monotonically and is practically negligible for distances $\gtrsim 1.4$ $R_M$. During perturbed times we observe peaks of flow densities at larger radii. In the case of the ICME this occurs at $\sim 1.25$ $R_M$, while in the case of the first SIR there are large peaks at distances up to 1.7 $R_M$.

In the next step, we multiply this flow density with the area of the ring with a radius $R_i$ and width $\Delta R$, where the latter is calculated as

![Figure 11. O$^+$ and O$^+_2$ velocities (red arrows) and densities (color coded) along selected Mars Express orbits in the terminator and meridional planes.](image-url)
\[ \Delta R_i = \frac{R_i - R_{i-1}}{2} + \frac{R_{i+1} - R_i}{2} = \frac{R_{i+1} - R_{i-1}}{2}. \]  

(2)

\( R_i, R_{i-1}, \) and \( R_{i+1} \) are MEX distances at successive times \( t_{i-1}, t_i, \) and \( t_{i+1}. \)

The area of the ring \( A_i \) is thus calculated as

\[ A_i = 2\pi R_i \Delta R_i. \]  

(3)

During perturbed times the large \( j \) values at large radial distances contribute most to the total flow since at these distances also the corresponding ring areas are largest.

Finally, we sum the flow over all measurements during the inbound portion of the orbits. In the Figure 13 we show the ion transterminator flow of \( O^+ \) and \( O_2^+ \). The \( O^+ \) values are represented with pink crosses, the \( O_2^+ \) values with yellow plus signs, while the total flow is presented with white triangles. SIR-perturbed and ICME-perturbed times are shaded in red and green, respectively.

The calculated flow varies greatly during perturbed times ranging between \( 8.3 \times 10^{21} \)–\( 8 \times 10^{23} \) particles per second. This is especially true for the flow during the passage of the first SIR when flows reach values up to a factor of \( \sim 4 \) (\( O^+ \)) and \( \sim 8 \) (\( O_2^+ \)) higher than those before the SIR arrival. During the ICME passage the flows are similar to those during quiet times, while they are enhanced again during the passage of the second SIR reaching values that are a factor of \( \sim 1.9 \) (\( O^+ \)) and \( \sim 4.7 \) higher than those during quiet times.

Next we look at the Figure 14 in which we show the \( O_2^+ / O^+ \) flow normalized to that of \( O^+ \). This ratio varies between 0.07 and 0.4 during quiet times. The highest values of up to 1.37 are observed during orbits when the first SIR was interacting with Mars. The \( O_2^+ / O^+ \) flow ratio during the ICME was 0.58 and that during the second SIR 0.53. This is somewhat higher than during quiet days.

Finally, Figure 15 shows the density of \( O_2^+ \) normalized to that of \( O^+ \). We calculate this ratio by following a similar procedure as for the flow calculation but without the multiplication by velocity. We can see that this ratio is \( \lesssim 0.6 \) for all orbits except for orbits \#4995–5002 when the first SIR was passing the planet. During this time the \( O_2^+ / O^+ \) density ratio reached the highest value of 2.2 during the orbit \#4998. It is interesting to note that during the times when ICME and the second SIR were passing the planet, this relative abundance was approximately the same as during quiet times.

5. Discussion

Here we compare the calculated BS and IMB distances and the transterminator flow properties to values from the existing literature.

We find that the BS location in the terminator plane varied by 0.8 \( R_M \), from 2.2–3 \( R_M \) (although during the inbound portion of orbit \#4997 the BS was not observed and was probably farther away from the planet) between November 20 and 27, 2007. This is more than the values reported by Edberg, Nilsson, et al. (2010) who found variations of 0.6 \( R_M \) during two time intervals in 2005 and 2007. These authors came up with the equation relating the terminator BS distance \( R_T \) and the SW magnetosonic Mach number (\( M_{ms} \)):

\[ R_T = -0.1M_{ms} + 3.3. \]  

(4)
From this we estimate the extreme $M_{ms}$ values at Mars during November 20–27, 2007 to vary between 11 and 3 during quiet and perturbed (first SIR) times, respectively. Both values could be considered as extreme according to the $M_{ms}$ distribution calculated by Edberg, Lester, et al. (2010) which shows that the average $M_{ms}$ at Mars is 8.1 and almost all values lies between 5 and 11.

The IMB distance in the terminator plane varied between 1.1 and 1.6 $R_M$, so by 0.5 $R_M$ or 45%. The lowest values were found during the passage of the first SIR and the ICME. This coincides with the fact that these two structures caused the largest increase of the $P_{dyn,SW}$ and it also agrees with reports on BS/MPB compression during high SW pressure conditions (Romanelli et al., 2018).

We should mention that in addition to $P_{dyn,SW}$ and the SW Mach number, there are other parameters that play an important role in the BS and IMB location variability. One of them is the solar EUV flux which may cause such variations on the order of days, years, and through the solar cycle (e.g., Hall et al., 2016, 2019). Short-term variations may be caused by solar flares (e.g., Fletcher et al., 2011). However, no flares were detected during the time period studied here. The second factor are crustal fields which were shown to have a small effect on the location of MPB (Bertucci et al., 2005; Crider et al., 2002), but cause the north–south asymmetry of the BS (Gruesbeck et al., 2018). The average IMB location variation on the southern hemisphere due to crustal fields has been shown by Crider et al. (2002) to be ~200 km. However, since the variations of the BS and IMB locations that we observe coincide with the arrival of the SW structures, we identify these structures to be the origin of the variations.

In contrast to, our transterminator flow values it is more common in the literature to report escape rates. Escape flow and transterminator flow are of similar magnitude. It was was shown by, for example, Ma et al. (2004) that about half of the transterminator flow escapes.

Nilsson et al. (2011) estimated the heavy ion ($O^+$, $O_2^+$ and $CO_2^+$) net escape rate from Mars. The escape flux was calculated to be $2 \times 10^{24}$ s$^{-1}$ which is similar to our highest estimate of transterminator flow of $\sim 1.2 \times 10^{24}$ s$^{-1}$ during the SIR-perturbed orbit #4999 and much higher than our lowest value of $3.4 \times 10^{22}$ s$^{-1}$ during the quiet-time orbit #4995.

Fränz et al. (2010) estimated escape flows of $O^+$ and $O_2^+$ for several orbits, among them also for orbits #5009 and #5010. Their values are almost two orders of magnitude higher than our estimates. Part of the reason has to do with the fact that these authors model the ion distribution function at low energies. In our case, however, the low energy ions are not taken into account. Due to this our densities may be underestimated and the same goes for flow densities and total flows.

Edberg, Nilsson, et al. (2010) estimated that during CIRs (a subset of SIRs) the heavy ion outflow from Mars increased by a factor of 2.5. Our transterminator flow values increase by a factor of $\sim 8$ ($O_2^+$) and $\sim 4$ ($O^+$), which is substantially higher.

6. Conclusions

In this work we study the interaction between SW structures (2 SIRs and 1 ICME) and Mars’ plasma environment during November 20–27, 2007, when the Sun was in prolonged minimum of its activity. At the time the
Hence we show that during solar minima the interaction of relatively moderate SW structures (SIR, ICME) with Mars’ plasma environment may result in large displacement of the IMB and the BS, in enhanced ion transterminator flow, and the variations of its $O_2^+/O^+$ ratio. Especially strong was the interaction with the Mars Express orbit number. The SIR-perturbed and ICME-perturbed times are shaded in red and green, respectively. The purple crosses, yellow plus signs and white triangles represent the $O^+$, $O_2^+$ and the total (the sum of the two) values, respectively.

Hence we show that during solar minima the interaction of relatively moderate SW structures (SIR, ICME) with Mars’ plasma environment may result in large displacement of the IMB and the BS, in enhanced ion transterminator flow, and the variations of its $O_2^+/O^+$ ratio. Especially strong was the interaction with the first SIR. This was the only structure intense enough so that it caused a Forbush decrease at Mars, as shown in the Figure 6. During the passage of this structure, the $P_{\text{dyn,SW}}$ increased by $\sim600\%$ and it was much higher than during the quiet times and somewhat higher than during the passage of the ICME and the second SIR. This is consistent with Curry et al. (2015), Edberg et al. (2009) and Nilsson et al. (2011) who showed that the ion escape increases with increasing $P_{\text{dyn,SW}}$. This points to the dynamic pressure probably being the most important parameter that governs the response of Mars’ plasma environment to SW perturbations.

Data Availability Statement
Authors acknowledge ClWeb (http://clweb.irap.omp.eu/), AMDA (http://amda.irap.omp.eu/) and ESA Planetary Science Archive Data (https://open.esa.int/esa-planetary-science-archive/) teams for easy access and visualization of the data.

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Figure 15. $O_2^+/O^+$ ratio as a function of the Mars Express orbit number during the inbound portions of the orbit. Transterminator flow below 2 $R_M$ during the inbound portion of the orbit as a function of the Mars Express orbit number. The SIR-perturbed and ICME-perturbed times are shaded in red and green, respectively. The purple crosses, yellow plus signs and white triangles represent the $O^+$, $O_2^+$ and the total (the sum of the two) values, respectively.
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