Recurrent Solar Energetic Particle Flux Enhancements Observed near Earth and Mars

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Abstract

The period 2016 August 1 to November 15 was characterized by the presence of corotating interaction regions (CIRs) and a few weak coronal mass ejections (CMEs) in the heliosphere. In this study we show recurrent energetic electron and proton enhancements observed near Earth (1 au) and Mars (1.43–1.38 au) during this period. The observations near Earth use data from instruments on board the Advanced Composition Explorer, the Solar and Heliospheric Observatory, and Solar Dynamics Observatory and those near Mars are from the Solar Energetic Particle, Solar Wind Ion Analyzer, and Magnetometer instruments on board the Mars Atmosphere and Volatile EvolutioN (MAVEN). During this period, the energetic electron fluxes observed near Earth and Mars showed prominent periodic enhancements over four solar rotations, with major periodicities of ~27 days and ~13 days. Periodic radar blackouts/weakens of radar signals at Mars were observed by the Mars Advanced Radar for Subsurface and Ionosphere Sounding/Mars Express, and are associated with these solar energetic electron enhancements. During this period, a weak CME and a high-speed stream (HSS)-related interplanetary shock could have interacted with the CIR and enhance energetic proton fluxes near 1.43–1.38 au, causing ~27 days periodicity in proton fluxes to be significantly diminished at 1.43–1.38 au. These events also have an unexpected impact on the Martian topside ionosphere, such as topside ionospheric depletion and compression observed by the Langmuir Probe and Waves and Neutral Gas and Ion Mass Spectrometer on board MAVEN. These observations are unique not only because of the recurring nature of electron enhancements seen at two vantage points, but also because they reveal the unexpected impact of the weak CME and interplanetary shock on the Martian ionosphere, which provides new insights into the impact of CME–HSS interactions on the Martian plasma environment.

Unified Astronomy Thesaurus concepts: Solar coronal mass ejections (310); Corotating streams (314); Solar particle emission (1517); Solar energetic particles (1491); Inner planets (797); Ionosphere (860); Mars (1007)

1. Introduction

Corotating interaction regions (CIRs) are structures formed by the interaction between slow and fast solar wind streams that primarily originate in solar coronal holes, which persist for several solar rotations. The CIRs or stream interaction regions (SIRs) are the most important source of space weather disturbances during the declining and minimum phases of a solar cycle. Coronal mass ejections (CMEs) are eruptions of plasma and magnetic field from the solar corona. In comparison to CIRs, they are short-lived transients, passing through the heliosphere with higher velocities. CMEs and CIRs are the major sources of energetic particles in the inner heliosphere. Recurrent CIR-accelerated ion events were previously observed by the Solar and Proton Telescope on board the twin Solar TErrestrial RElations Observatory (STEREO) spacecraft during the late phase of solar cycle 23 (Gómez-Herrero et al. 2009). Interplanetary CMEs (ICMEs); interplanetary manifestation of CMEs typically remote-sensed by coronagraphs) are the major drivers of extreme space weather events on planets and occur more frequently during the solar maximum phase. However, there are exceptions, like the large number of eruptions that occurred between 2017 September 4 and 10 September, including four eruptions associated with X-class flares in the decay phase of solar cycle 24, which affected Earth (Luhmann et al. 2018) and Mars (Lee et al. 2018). The declining phase of the weak solar cycle 24 is actually characterized by the presence of several slow CMEs, that is, CMEs with speeds below the typical solar wind speed of ~400 km s⁻¹ (e.g., see the near-Earth ICME list, http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm, compiled by Richardson and Cane Richardson & Cane 2010), as well as by the occurrence of coronal holes, especially over low latitudes. Therefore, an interaction between slow/weak CMEs and a high-speed stream (HSS) is expected to happen during the late phase of solar cycle 24.

The interaction of such slow/weak CMEs with other CMEs or the HSS can significantly change their properties while it propagates through the heliosphere (Heinemann et al. 2019) and alter the geoeffectiveness (Gopalswamy et al. 2009; He et al. 2018). There are studies that show that when two CMEs occur within ~12 hr, the probability of having the second CME be Solar Energetic Particle (SEP)-rich is quite high (Gopalswamy et al. 2002, 2004). These studies also show that the CMEs with intense SEP enhancements are more likely to be preceded by another CME eruption (Kahler & Vourlidas 2005), though the exact process by which this interaction occurs is still not very clear. When CIRs and ICMEs interact, they can also form merged interaction regions (MIRs). Radial propagation and expansion of slow CMEs sometimes leads to formation of shocks (Luczak et al. 2017), and slow CMEs are accelerated during interaction with an HSS in the heliosphere (Gosling & Riley 1996). However, the impact of such CME–SIR interactions on the SEP characteristics, as observed at different observer locations, is not well understood. Similarly, how the CME–HSS interactions might modify their impacts on Martian plasma environment has yet been understood.

Low solar activity affects the plasma system at Mars (Ramstad et al. 2015; Hall et al. 2016; Sánchez-Cano et al. 2016). During a
solar minimum phase in March 2008, an ICME and SIR events impacted Mars and caused a strong compression of the magnetosheath and ionosphere (Sánchez-Cano et al. 2017). The dynamic response of the Martian ionosphere to a CIR-related interplanetary shock (IPS) was studied by Harada et al. (2017). They found that subsequent to the sudden dynamic pressure enhancement, radar soundings recorded disturbed signatures in the topside ionosphere. In this study, we present observations of the periodic enhancements of solar energetic particles from vantage points near Earth (1 au) and near Mars (during this period, Mars was between 1.43 and 1.38 au, and the mean distance is 1.405 au), for four consecutive solar rotations during 2016 1 August–15 November, along with observations of CME and HSS, and their impacts on the Martian plasma environment. This study is important because we do not have much information on how Mars is affected by space weather during the solar minimum, especially by CME–HSS interactions.

2. Data and Methods

The solar observations are taken from the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO)-C2. These images show the presence of coronal holes as well as CME eruptions. We have also used the Wang–Sheeley–Arge (WSA)–ENLIL model (Odstrcil 2003; Mays et al. 2015) to numerically simulate the interplanetary solar wind plasma and magnetic field conditions, for a global heliospheric context for the solar events discussed, as well as for the relative planetary positions. The simulations used in the study are taken from ENLIL Solar Wind Prediction. The simulations show the arrival of the HSSs at both Earth and Mars, for four consecutive solar rotations and the arrival times coincide with the observed SEP electron enhancements.

The energetic particle measurements at the first Lagrangian point of the Sun–Earth system (L1) for the selected events are from the Electron Proton Alpha Monitor (EPAM) sensor on board the Advanced Composition Explorer (ACE; Gold et al. 1998). These data are obtained from the ACE data center. The deflected electrons (DE) sensor measures electron fluxes in 4 energy channels, that is, 0.038–0.053 MeV, 0.053–0.103 MeV, 0.103–0.175 MeV, and 0.175–0.315 MeV. The EPAM sensor also provides proton fluxes in the energy range from 47 keV to 4.75 MeV, in eight channels; here we have used the ion fluxes measured in four channels in the energy ranges 0.31–0.58 MeV, 0.58–1.05 MeV, 1.05–1.89 MeV, and 1.89–4.75 MeV by the Low Energy Magnetic Spectrometer (LEMS) of the EPAM sensor. The ACE Solar Wind Electron Proton Alpha Monitor (SWEPAM) and magnetic field experiment measurements are used for interplanetary magnetic field (IMF) and solar wind speed observations at 1 au.

The data sets from the Mars Atmosphere and Volatile Evolution (MAVEN) instruments are from the the Planetary Data System. The solar wind speed and IMF values at 1.43–1.38 au are obtained from the Solar Wind Ion Analyzer (SWIA; Halekas et al. 2015) and Magnetometer (MAG; Connerney et al. 2015) instruments on board MAVEN. SWIA is an energy and angular ion spectrometer that measures the energy and angular distributions of solar wind ions of energy between 25 eV and 25 keV with 48 logarithmically spaced energy steps. MAG is a fluxgate magnetometer that measures the intensity and direction of the IMF. The SWIA onboard moments and MAG measurements are used to compute the upstream solar wind and magnetic field parameters using the method by Halekas et al. (2017). The method is based on the measured bulk flow speed $|v|$, proton solar temperature $T$, latitude $R$, and normalized magnetic field fluctuation levels $\sigma_R / |B|$, where $\sigma_R$ is the root-sum-squared value of the $32 \text{ Hz}$ fluctuation levels in all three magnetic field components over a 4 s interval. To select undisturbed solar wind intervals, points with $|v| > 200 \text{ km} \text{s}^{-1}$, $\sigma_R / |B| < 0.15$, $R > 500 \text{ km}$, and $\sqrt{T} / |v| < 0.012$ are chosen (Halekas et al. 2017). In the later phase, that is, after ~ October 20, 2016, the orbit of MAVEN was inside the Martian bow shock, hence it was not observing the “pure” solar wind condition, therefore the solar wind speed and IMF could not be deduced. Level 2, version 01, revision 01 (V01_R01) data of SWIA, and level 2, version 01, revision 01/02 (V01_R01/R02) data of MAG, are used for analysis.

The SEP fluxes are obtained from the Solar Energetic Particle (SEP) instrument on board MAVEN. This instrument consists of two identical sensors, SEP 1 and SEP 2, each consisting of a pair of double-ended solid–state telescopes to measure 20 keV–200 keV electrons and 30 keV–6 MeV ions in four orthogonal view directions (Larson et al. 2015). The data used in this study are the ion and electron data in the form of differential energy fluxes measured by the SEP 1 sensor in the 1F direction, which typically views the Parker spiral direction (Larson et al. 2015). Both SEP 1 and SEP 2 sensors in the forward and reverse facing fields of view observed the recurrent SEP enhancements. The Level 2, version 04, revision 02 (V04_R02) data of SEP are used. The Langmuir Probe and Waves (LPW; Andersson et al. 2015) instrument on board MAVEN is used for the in situ electron density measurements [Level 2, version 3, revision 01 (V03_R01)]. The electron densities in the LP mode are derived based on I–V characteristics. The Neutral Gas and Ion Mass Spectrometer (NGIMS; Mahaffy et al. 2014) observations of MAVEN are used to understand the variations of $O^+$ and $O^+$ ion densities in the Martian ionosphere. NGIMS is a quadrupole mass spectrometer that measures the composition of neutrals and thermal ions, in the mass range 2–150 amu with unit mass resolution. NGIMS level 2 ion data, version 08, revision 01 (V08_R01), are used.

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) on board the Mars Express (MEX) is a nadir-looking pulse-limited radar sounder operating at both active ionospheric sounding (AIS) as well as subsurface sounding modes (Gurnett et al. 2008; Orosei et al. 2015). MARSIS consists of a 40 m antenna, with an associated radio transmitter and receiver. In AIS mode, the operation is that of a swept-frequency radar sounder, with 160 frequencies chosen from 0.1 to 5.5 MHz in roughly logarithmic spacing. The transmitter sends a 91 $\mu$ s tone at 127 pulses per second rate. The frequency sweep takes 7.3 s to complete the 0.1–5.5 MHz range (Orosei et al. 2015). Even in the AIS mode, the transmitted frequencies can be reflected from the Martian surface if they are larger than the critical plasma frequency of the Martian ionosphere. However, this is true only for the terminator and nightside observations, while the signal absorption at lower solar zenith angles such as <70 deg. could be due to the
absorption by the robust Martian dayside ionosphere. For the present study, we have used data from the AIS mode, but the echoes corresponding to the 4 MHz frequency are actually due to the surface reflections. The MARSIS/MEX data are given in the PDS-3 format and are obtained from the ESA Planetary Science Archive (ESA PSA).10

3. Overview of Events

Figures 1(a)–(d) show the presence of persistent coronal holes on the solar disk, as seen in the 193 Å image from AIA on board SDO. These are the sources of the continuous HSS resulting in corotating interaction region events. Due to the similar relative observer positions for Earth and Mars during this period, we can consider these stationary heliospheric observers. As the coronal hole source continuously emits high-speed streams, the streams will hit the observers with a ∼27 day rotation period of the Sun. The arrival of these streams corresponds to enhancements in the SEP fluxes, observed at both the L1 point and near Mars (see Table 1). The differences in the stream arrival times are consistent with the relative location of the planets in the heliosphere, and the heliolongitude of the source location. Figure 1(e) shows a snapshot of a CME eruption observed by the LASCO C2 coronagraph during 2016 August 9–October 20, (DN 69 to 70, where DN denotes the day number from 2016 August 01). There were no obvious signatures in the low corona, therefore this is probably a “stealth CME” (He et al. 2018). Unlike a typical CME eruption that leaves one or more signatures in the solar disk, a stealth CME will have no obvious low coronal signature. The AIA images suggest that there are coronal holes near the solar equator during this time (He et al. 2018). The HSS from the coronal holes may influence the propagation of the CME in the heliosphere (Liu et al. 2016). However, the arrivals of the HSS and the CME eruption at both the planets are marked by distinct enhancements in SEP fluxes, as described later. Also, there was an HSS-related interplanetary shock during 17 to 20 September (DN 48 to 51). The science events listed by the MAVEN science data center11 show the arrival of interplanetary shock and low-energy SEP ions accelerated by a strong solar wind stream during this period. In addition to these, there were weak/moderate CME eruptions during the beginning of August, toward the end of September, and in early October, some of which were west–limb eruptions, and these might have been additional sources of SEPs at Earth and Mars, through magnetic connections.

Figure 2 shows the WSA-ENLIL simulation snapshots during the passage of CIR (at Earth) for four consecutive solar rotations, as well as during the IPS/HSS event at Earth. Mars was behind the Earth and observed the CIR/HSS first compared to Earth, owing to the counterclockwise rotation of the Sun. The stealth CME event of 8–9 October is not captured in the general simulation. However, the CME event is observed by SOHO/LASCO-C2, which is shown in Figure 1(e). The time-dependent WSA-ENLIL+Core global 3D MHD model with graduated cylindrical shell (GCS) results as input (including the time when the CME crosses the inner boundary at 21.5 R.) captures the presence of this stealth-type CME, as shown in Figure 6 of He et al. (2018). Table 1 shows the times at maximum solar wind speed, IMF B⊥, and SEP intensities are observed at Earth and Mars during the prominent events of the period (for the case of CIR/HSS events, the time given is the time of maximum solar energetic electron intensities observed, while for the CME event, the time given is the time of maximum solar energetic proton intensities observed, because during the CME event the proton enhancement is more prominent).

Figure 3(a) shows the variation of IMF and solar wind speed as observed at the L1 point (near Earth) by ACE, during 2016 August 1–15 November (DN 1 to 107). The day numbers marked on the x-axis start from 2016 August 1 and subsequent plots follow that convention. Periodic enhancement in solar wind speed is seen as a result of the periodic arrivals of the high-speed streams. The z-component of the IMF and the total B show the largest fluctuations coincident with the arrival of the CIRs, followed by fluctuations of smaller magnitude, a typical feature of CIR events near 1 au (Borovsky & Denton 2006). Here B, is also shown to infer when the IMF turns southward, which would cause a magnetic reconnection and a geoeffective storm. Figure 3(b) shows the variation of IMF and solar wind speed as observed by the MAG and SWIA instruments on board MAVEN, located near 1.43–1.38 au. The total magnetic field increases coincident to the arrival of the HSS. The solar wind speed shows periodic enhancements similar to that observed near Earth. In addition to the stream arrivals, there are clear signatures of the interplanetary shock and CME arrivals at both locations during 17–18 September (DN 48–49) and 2016 14–15 October (DN 75–76), respectively. The event arrivals can be identified with the enhancements in solar wind speed and magnetic field (Figure 3(b)).

4. Solar Energetic Particle Observations

Figure 4(a) shows the variation of the energetic electron flux in the energy range from ∼30 keV to ∼315 keV and Figure 4(b) shows the variation of the energetic proton flux in the energy range from ∼320 keV to ∼4.8 MeV, both observed by the EPAM sensor on board ACE located at the L1 point near Earth. Four distinct peaks are seen in the electron fluxes up to 100 keV, and all these enhancements were significantly above the quiet-background levels. The proton fluxes are smaller in magnitude compared to the electron fluxes during all these major peaks (Figure 4(b)). However, note that the proton enhancement signature is also prominent on 2016 August 3 (DN 3), October 10 (DN 71), and October 16 (DN 77), and there is still minor proton enhancement on 2016 September 17 (DN 48).

Figure 4(c) shows the variation of the energetic electron flux in the energy range from ∼30 keV to ∼200 keV and Figure 4(d) shows the variation of the energetic proton flux in the energy range from ∼340 keV to ∼5 MeV, both observed by the SEP instrument on board MAVEN located at 1.43–1.38 au, near Mars. The signature of the periodic enhancements is seen here as four distinct peaks in the electron fluxes, in all three channels up to ∼200 keV. Figure 4(d) shows the corresponding proton enhancements, measured by MAVEN/SEP. The proton fluxes here are smaller in magnitude compared to the electron fluxes during all the major peaks, but the enhancements are clearly above the quiet-background time fluxes in all channels. Near 1.43–1.38 au, the fluxes are enhanced by a factor of ∼20, compared to the proton fluxes observed at 1 au. Electrons also show enhancement as they reach 1.43–1.38 au, but to a lesser extent (<10 times, between 1 and 1.43–1.38 au). Among the four enhancements, the first and third SEP enhancements could have contributions from CME.

10 https://www.cosmos.esa.int/web/psa/Mars-express
11 https://lasp.colorado.edu/maven/sdc/public/
Figure 1. (a)–(d) Images of the coronal hole on the solar disk by SDO/AIA for four successive solar rotations: (a) August 2 (DN 2), (b) September 2 (DN 33), (c) 29 September (DN 60), (d) October 26 (DN 87). (e) Difference image from the SOHO LASCO C2 coronagraph superposed with an Extreme ultraviolet Imaging Telescope image showing a weak CME eruption on October 9 (DN 70). DN: day number from 2016 August 1.
eruptions during the beginning of August and during the end of September. The second and fourth enhancements can be considered as only being due to CIR events. However, as mentioned earlier, there are eruptions during the end of September that are mostly associated with the west–limb CME event and the SEPs arrive at the observers through magnetic connection of the CME-accelerated shock source. The magnetically connected SEP intensities are often found to be an order of magnitude lower than the SEPs coming directly to the observer location (Xie et al. 2017), therefore their contributions to the major CIR/SIR related enhancements would be secondary in nature.

Apart from the four major enhancements related to CIR arrivals mentioned above, there are two other enhancements. The first one peaks on 18 September (DN 49) and the second

Table 1

| Event      | Peak time at Earth [DN (month/day, hh:mm)] | Peak time at Mars [DN (month/day, hh:mm)] |
|------------|-------------------------------------------|-------------------------------------------|
| CIR-1      | 9 (Aug 9, 12:00) 9 (Aug 9, 09:00) 9 (Aug 9, 06:42) | 6 (Aug 6, 21:27) 7 (Aug 7, 13:55) 7 (Aug 07, 15:21) |
| CIR-2      | 34 (Sep 3, 16:04) 36 (Sep 5, 16:04) 36 (Sep 5, 08:52) | 33 (Sep 2, 17:45) 34 (Sep 3, 20:52) 35 (Sep 4, 20:38) |
| IPS/HSS    | 51 (Sep 20, 11:02) 50 (Sep 19, 18:57) 51 (Sep 20, 19:12) | 49 (Sep 18, 08:09) 48 (Sep 17, 23:45) 49 (Sep 18, 07:26) |
| CIR-3      | 65 (Oct 4, 11:00) 65 (Oct 4, 12:00) 63 (Oct 2, 02:52) | 62 (Oct 1, 16:33) 61 (Sep 30, 11:45) 61 (Sep 30, 11:45) |
| CME        | 74 (Oct 13, 01:55) 74 (Oct 13, 22:04) 73 (Oct 12, 03:07) | … … 76 (Oct 15, 07:12) |
| CIR-4      | 90 (Oct 29, 07:55) 90 (Oct 29, 00:57) 91 (Oct 30, 13:12) | … … 87 (Oct 26, 02:09) |

Figure 2. WSA-ENLIL simulation snapshots during CIR-1 (August 9, DN 9), CIR-2 (September 3, DN 34), CIR-3 (October 4, DN 65), CIR-4 (October 29, DN 90), and IPS/HSS (20 September, DN 51) events at Earth. DN: day number from 2016 August 1.
enhancement peaks on October 15 (DN 76) at Mars (Table 1). Electron enhancements are also seen on these days, but with much shorter duration. These enhancements are possibly related to the interplanetary shock during September 17–20 (DN 48 to 51) and a weak CME eruption on 2016 October 8–9 (DN 69 to 70, Figure 1(e)), whose SEPs arrive at Earth and Mars on October 12 and 15 (DN 73 and 76) respectively (Table 1). It is seen that a very weak CME could enhance SEPs
to a significant level. The peaks of these enhancements are only approximately an order of magnitude lower than the SEP event observed at Mars by MAVEN (Jakosky et al. 2015; Thampi et al. 2019). Other minor enhancements in solar wind parameters and energetic particle flux during the period could be due to the transient fast solar wind and accelerated population of interplanetary/solar wind particles (Prinsloo et al. 2019).

To estimate the periodicities and the amplitudes of the signals with different frequencies (periods), we have performed a Fast Fourier Transform (FFT) analysis of the solar wind at the L1 point and the SEP fluxes observed near 1 and 1.43–1.38 au. Daily values are used for this analysis after removal of the mean. The solar wind speed observations near Mars were not subjected to this analysis because of the limited data length. Figures 5(a) shows the FFT spectra of the solar wind at L1 point near Earth. Quasi 27, quasi 13, and quasi 9 day periodicities are significantly observed, as previously reported by Tulasi Ram et al. (2010) for the CIR observations during the 2008 period, which was the declining phase of the previous solar minimum. Figure 5(b) shows the FFT spectra of SEP electrons and protons (for protons with amplitudes multiplied by 100, for clarity in visualization) observed by ACE. The electron flux spectra show the highest amplitude for the quasi 27 day, followed by the quasi 13 day period. Figure 5(c) shows the FFT spectra of SEP electrons and protons (shown in the figure with multiplication by 100 for protons) observed by MAVEN. Here the electron flux spectra show the highest amplitude for the quasi 27 day, followed by the quasi 13 day periodicity. This confirms that the SEP electron enhancements are predominantly caused by the SIR/CIR during this period, and the transient CME eruptions could not distort the periodic nature of the electron enhancements.

The periodicities in proton fluxes near 1 au (Figure 5(b)) are of much lesser amplitude compared to that of electrons, but the quasi 27 day one is the most prominent. Interestingly, the FFT analysis of proton fluxes near 1.43–1.38 au (Figure 5(c)) shows that the quasi 27 day periodicity is completely diminished, whereas the quasi 13 day and quasi 9 day periods are above the 95% significance level. Also, the periodicities have less amplitude compared to that in electron fluxes. Here, the weak transient CME eruptions and their interaction with SIRs could diminish/completely distort the periodic nature of the proton enhancements.

5. Impacts on Mars

Figures 6(a)–(f) show examples of the variation of the 4 MHz signal of the MARSIS radar during the AIS mode operations. The time delay experienced by the signal is shown on the left y-axis and the apparent range is shown on the right y-axis. The along-track change in satellite altitude and solar zenith angle (SZA) are also shown. The color bar represents the signal strength in units of spectral density. Reflected signals at these frequencies (>3 MHz) are basically reflections from the Martian surface (Morgan et al. 2014), especially for solar zenith angles >70 deg. Representative examples showing normal signals, blackout, and weak signals are given. During the CIR-3 arrival, there is a complete blackout of the radio signal, whereas during the CIR arrivals 1, 2, and 4, the signals were significantly weak, indicating partial absorption. However, observations during CIR-2 were on the dayside and close to the terminator, where signal attenuation at SZA < 70 deg. could be mostly due to dayside absorption, which is true for all observations at lower solar zenith angles. The variations of signals at other frequencies above 3 MHz, such as 3.5 MHz,
4.5 MHz, and 5 MHz, are similar to the variation at 4 MHz (hence they are not illustrated).

Figure 7 shows the impact of the interplanetary shock and weak CME events on the Martian ionosphere. The left panels (Figures 7(a), (c), (e)) show the LPW—$$e^+$$, NGIMS—$$O_2^+$$, and $$O^+$$ profiles corresponding to the September 17–18 (DN 48–49) interplanetary shock event, and the right panels (Figures 7(b), (d), (f)) show the LPW—$$e^+$$, NGIMS—$$O_2^+$$, and $$O^+$$ profiles corresponding to the October 14–15 (DN 75–76) stealth CME event (caused by the CME eruption during 8–9 October). Figure 7(a) shows the electron density profiles during 2016 September 17 to 18, along with the quiet-time profiles (several orbits on September 15, 16, and 20) with their mean and standard deviation. Orbits 3835, 3836 (September 17), and 3837 (September 18) show deviation compared to the mean quiet-time profile. The ionopause (the ionospheric boundary, where the ionospheric pressure balances the solar wind dynamic pressure) altitudes observed for these three orbits are below 400 km. The next orbit, 3838 on September 18, shows normal behavior. The $$O_2^+$$ and $$O^+$$ profiles (Figures 8(c) and (e)) show a similar variation, with an ionopause below 400 km. It must be noted that NGIMS alternates between ion and neutral modes, whereas LPW measures the electron density in all orbits, hence the signature is seen only in one orbit in NGIMS data. The magnetic field started to enhance from the quiet-time values on September 17 ~18 UTC, and maximized at 23 hours and 40 minutes UTC to 13.3 nT. The responses seen in LPW profiles are concurrent with these enhancements. Similar features can be seen during the CME event (2016 October 14–15) as well. Here the typical quiet orbits are taken from several orbits on October 12, 13, and 16. The LPW electron data during the event orbits show deviation from the quiet-time profiles for three consecutive orbits (Figure 7(b)) and the NGIMS $$O_2^+$$ and $$O^+$$ profiles show differences from the quiet-time behavior in two profiles (Figures 7(d) and (f)), on October 14 and 15. Though solar wind magnetic field data are not available during this period, from the arrival times of the CME and the analysis on the CME–HSS interaction reported by He et al. (2018), it can be concluded that the depletion and compression seen in the topside ionosphere are the consequence of the weak CME. The shock of the CME structure arrives first, along with the energetic particles, and subsequently the CME sheath region arrives with fluctuations in the IMF. The compression of the Martian magnetosphere–ionosphere system is observed during the entire period of passage of CME structure and associated energetic particles (Jakosky et al. 2015).

6. Discussion

The CIRs are often associated with shocks, when electrons are accelerated, as observed by the Ulysses spacecraft when it was exploring the three-dimensional heliosphere between 1 and 5 au during the declining phase of solar activity (Mann et al. 2002). A field-aligned flux of energetic electrons with energies up to ~200 eV or higher is commonly observed upstream from both the forward and reverse shocks that bound CIRs at heliocentric distances greater than ~2 au (Gosling et al. 1993). Ulysses observations confirmed that the majority of the periodic energetic particle increases are due to particles accelerated at long-lived CIRs that persisted over several solar rotations. During all four enhancements observed in the present study, electron fluxes measured near 1 au and 1.43–1.38 au were higher compared to those of ions, indicating that these are electrons that are accelerated at the reverse shock and re-entered the inner heliosphere; these electrons mirror to the reverse shock and get repeatedly accelerated. This process is less effective for the ions.
Simnett & Roelof 1995, which may explain the much lower ion fluxes. These observations provide evidence that the SEP electrons that are accelerated at the reverse shock are mainly associated with CIRs. These electrons counterstream to the inner heliosphere and again mirror to the reverse shock to get significantly accelerated, retaining their recurrent nature even in the presence of intermittent slow CMEs. However, the observed energetic proton enhancements are probably more influenced by the CME–SIR interactions.

The SEP electrons caused blackout/weakening of radio signals, as evident in the MARSIS observations. Previously, long duration HF radar blackout was observed by MARSIS and SHARAD (Mars SHAllow RADar sounder) during the very intense space weather event of 2017 September (Simnett & Roelof 1995). The loss of signal was interpreted the formation of an ionospheric layer near ~90 km, that absorbed HF radar signals similar to the D-region absorption in the terrestrial ionosphere. Theoretical calculations showed that this ionospheric layer is created by SEP electrons (rather than SEP protons), as previously proposed (Sánchez-Cano et al. 2019). Though recurrent geomagnetic activity due to CIRs was previously reported for Earth’s ionosphere (Tsurutani et al. 1995; Tulasi Ram et al. 2010), this kind of recurrence of energetic electron enhancement associated with CIRs and their impacts has not been reported from a vantage point near Mars, except for by Morgan et al. (2010), who showed two radar signal absorption events, separated by an interval of approximately 27 days, corresponding to one solar rotation. In this

Figure 7. (a), (c), and (e): MAVEN observations for the 2016 September CME event. (a) LPW measurements of electron density variation during the CME period—2016 September 17 and 18 (DN 48 and 49) along with “quiet” orbits—2016 September 15, 16, and 20 (DNs 46, 47, and 51) and their mean and standard deviations. (c) and (e): NGIMS $O_2^+$ and $O^+$ variation during the CME period—2016 September 17 and 18 (DN 48 and 49) along with “quiet” orbits—2016 September 15, 16, and 20 (DN 46, 47, and 51). (b), (d), and (f): MAVEN observations for the 2016 October event. (b) LPW measurements of electron density variation during the CME period—2016 October 14 and 15 (DN 75 and 76) along with “quiet” orbits—2016 October 12, 13 and 16 (DN 73, 74, and 77) and their mean and standard deviations. (d) and (f): NGIMS $O_2^+$ and $O^+$ variation during the CME period—2016 October 14 and 15 (DN 75 and 76) along with “quiet” orbits—2016 October 12, 13 and 16 (DN 73, 74, and 77).
the directly detected ion enhancements were only observed during the first event, whereas energetic electron enhancements were not reported. The events presented here clearly indicate that periodic radar blackouts during CIRs are associated solar energetic electron enhancements and this might have a major space weather impact on Mars during the declining phase of solar activity.

The interplanetary shock associated with the HSS during September 17–18 (DN 48–49) could significantly alter the Martian plasma environment by compressing the ionospheric boundary to lower altitudes (Figures 7(a), (c) and (e)). The geoeffectiveness of this interplanetary shock at Earth was less due to the magnetic field configuration, because the geomagnetic activity is linked to the southward IMF (Gosling et al. 1991). This period was also characterized by a HSS-stealth CME interaction event (October 12–15). The CME–HSS interaction during this event was studied in detail by He et al. (2018), who found that a weak CME without obvious signatures in the low corona could produce a relatively intense geomagnetic storm at Earth. Within the ICME, the total B characterised by a HSS-stealth CME interaction event was as high as 25 nT, while the southward IMF reached −21 nT, on 13 October (He et al. 2018). During this event, the CME propagating into an ambient solar wind was followed by an HSS on 13 October and a strong geomagnetic storm at Earth. Within the ICME, the total B characterised by a HSS-stealth CME interaction event was as high as 25 nT, while the southward IMF reached −21 nT, on 13 October (He et al. 2018).

Previously, it was reported that the presence of a CME a few hours before a fast eruption indicated higher fluxes of solar energetic protons, whereas the CME–CME interaction occurring within the solar corona is often associated with unusual radio bursts, indicating electron acceleration (Gopalswamy et al. 2002, 2004; Lugaz et al. 2017). It has also been reported that the trajectory of CMEs is significantly affected when the eruptions occur in close proximity to coronal holes, and leads to driverless shocks for purely geometrical reasons (Gopalswamy et al. 2009). In the present case, the interaction of the weak CME with SIR/CIR could be the cause of the enhanced SEP fluxes associated with the weak CME events. Note that He et al. (2018) provides evidence of a CME–SIR/CIR interaction for the October event, and show that the very slow CME of 2016 October 8–9 October was compressed, since it is bracketed between a slow and fast wind, hence producing a geomagnetic storm at Earth. Our study shows that the Martian topside ionosphere was also impacted by this event (Figures 7(b), (d), (f)).

It is understood that observations show that the Martian ionopause-like density gradient is seen at lower altitudes during CME events (Vogt et al. 2015; Thampi et al. 2018) as well as during CIRs (Lee et al. 2017; Krishnaprasad et al. 2019). However, previous reports were for intense CME and CIR periods (like 2015 March, 2015 June, and 2017 September event periods). Sánchez-Cano et al. (2017) studied the response of the Martian plasma environment to an ICME during the solar minimum period of 2008 March, whose dynamic pressure was less than 10 nPa, based on a proxy measurement from 1 au by STEREO-B. A large compression of the magnetosphere and ionosphere was observed, but on a smaller scale compared to events during moderate and high solar activity conditions. The novel observation here is that, to a similar extent, the topside ionospheric response to these intense events is caused by a relatively weak CME and an interplanetary shock. The maximum dynamic pressure for the interplanetary shock event was ∼9 nPa, while the peak dynamic pressure of the 2015 March 8 CME event was ∼15 nPa. However, as mentioned earlier, we do not have upstream dynamic pressure observations during the stealth CME event. This shows that the interplanetary evolution of CMEs, including slow ones can be quite complicated, as shown by interactions with the highly structured solar wind (Gopalswamy et al. 2001; Lugaz et al. 2012). The present study shows that since the combination of different solar wind structures can result in enhanced geoeffectiveness (Liu et al. 2014), the impact on nonmagnetized planets like Mars can also be enhanced by the CME–HSS interaction. This will have significant implications for calculations of ion escape from Mars, since a weak or declining phase of the solar cycle does not necessarily suggest lower impact or less erosion at the topside Martian ionosphere.

### 7. Summary

Recurrent energetic particle enhancements were observed on Earth and Mars, and both were nearly radially aligned in the ecliptic plane, during the period between 2016 August 1 and November 15 in the declining phase of solar cycle 24. These corotating events are HSSs forming SIR/CIR, and are due to the appearance of a stream producing a coronal hole in the solar disk for four consecutive solar rotations. Several spacecraft, such as ACE and MAVEN, simultaneously observed the arrival of SEPs during this period, with major periodicities of quasi ∼27 day and quasi ∼13 days. These CIR events were prominently energetic electron events, probably due to the reverse shock acceleration of electrons in CIR. Radio blackout/partial absorption of radio signals at Mars were observed by the MARSIS radar on board MEX during the energetic electron enhancements. These observations suggest that solar energetic electrons could be causing radio blackouts, in contrast to proton-rich events, as reported by Sánchez-Cano et al. (2019) using numerical calculations.

Interestingly, an HSS-related interplanetary shock and a weak CME, in 2016 September and October, respectively, interacted with the SIR/CIR structures forming a merged interaction region in the inner heliosphere. These interaction events produced enhancement in proton intensities at Earth and Mars, making the weak CME and the interplanetary shock have larger impacts on these planets, such as a decreased ionopause plasma boundary height at Mars, as observed by LPW and NGIMS on board MAVEN. The interaction also caused quasi–27 day periodicity to be completely diminished for solar energetic protons at 1.43–1.38 au (near Mars) in comparison to 1 au (near Earth).

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