Solar Energetic Particle Events of July 2017: Multi-spacecraft Observations near 1 and 1.5 au

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Abstract

We investigate the space weather events of late solar cycle 24 in July 2017 observed by a number of spacecraft in the inner heliosphere widely separated in heliolongitude and radial distance. These include spacecraft at L1 point, STEREO-A, near Earth satellites, and MAVEN (near Mars). The GRASP payload onboard Indian GSAT-19 satellite provides a new vantage point for Solar Energetic Particle (SEP) observations near Earth. There were two major Coronal Mass Ejections (CMEs) and one Stream Interaction Region (SIR) event in July 2017. The 16 July CME was Earth directed and the 25 July CME was STEREO-A and Mars directed. Earth and Mars were on the opposite sides of the solar disk, while Mars and STEREO-A were aligned with respect to the nominal Parker spiral field. The 25 July event was more stronger and wider in heliolongitude. This CME shock had magnetic connectivity to Earth, which produced an SEP event at Earth ~two days later. The spectral indices of the event observed directly at STEREO-A and remotely at ACE was found to be similar. The 17 July SIR event was observed by both MAVEN and STEREO-A. Higher particle intensities (a factor of 6 enhancement for 1 MeV ions) are observed by MAVEN (at 1.58 au) compared to STEREO-A (at 0.96 au). Also a spectral hardening is observed while comparing the spectral indices at these two locations, indicating an acceleration of energetic ions in SIR shock during the radial propagation of 0.62 au in the interplanetary space.

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9 Key Points:

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10	•	Multi-spacecraft observations of the solar events of late solar cycle 24 in July 2017
11		are presented. Observations near Earth, STEREO-A, and near Mars are used.
12	•	Solar Energetic Particle (SEP) proton enhancement is observed at a remote observer
13		location due to IMF connectivity with a distant CME-driven shock.
14	•	Spectral analysis of the SEP events associated with CMEs and SIRs are carried out
15		and the spectral features are interpreted in terms of acceleration, transport, and
16		magnetic connectivity.

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17 Abstract

We investigate the solar events of late solar cycle 24 in July 2017 observed by a number 18 of spacecraft in the inner heliosphere widely separated in heliolongitude and radial distance. 19 These include spacecraft at L1 point, STEREO-A, near Earth satellites, and MAVEN (near 20 Mars). The GRASP payload onboard Indian GSAT-19 satellite provides a new vantage 21 point for Solar Energetic Particle (SEP) observations near Earth. There were two major 22 Coronal Mass Ejections (CMEs) and a Stream Interaction Region (SIR) event in July 2017, 23 which is a period during the deep descending phase of the historically weak solar cycle 24. 24 The 16 July CME was Earth directed and the 24 July CME was STEREO-A and Mars 25 directed. Earth and Mars were on the opposite sides of the solar disk, while Mars and 26 STEREO-A were aligned with respect to the nominal Parker spiral field. The 24 July event 27 was stronger and wider in heliolongitude. This CME-driven shock had magnetic connectivity 28 to Earth, which produced an SEP event at Earth \sim two days later. The spectral indices of 29 the event observed directly at STEREO-A and at the remote location of ACE was found to 30 be similar. The 16 July SIR event was observed by both MAVEN and STEREO-A. Higher 31 particle intensities (a factor of 6 enhancement for 1 MeV protons) are observed by MAVEN 32 (at 1.58 AU) compared to STEREO-A (at 0.96 AU). Also a spectral hardening is observed 33 while comparing the spectral indices at these two locations, indicating proton acceleration 34 at the SIR forward shock during the radial propagation of 0.62 AU in the interplanetary 35 space. 36

37 1 Introduction

Solar Energetic Particles (SEPs) are the high energy protons, electrons, alpha particles, 38 and heavy ions released from the Sun and accelerated at or near the Sun or in the heliosphere 39 (e.g. recent reviews by Desai and Giacalone (2016); Klein and Dalla (2017)). These particles 40 are of energies in the range tens of keV up to a few GeV. Solar flares, Coronal Mass Ejections 41 (CMEs), and Stream Interaction Regions (SIRs) are major sources of energetic particles 42 in the inner heliosphere. Interplanetary acceleration by SIR and interplanetary shocks 43 can further act on SEPs to modify their properties. CMEs are ejection of plasma and 44 magnetic field from the solar corona, typically remote-sensed by coronagraphs. SIRs are 45 interaction regions formed in the heliosphere when the high velocity portion of a trailing 46 stream overtakes the low velocity region of the preceding stream (Smith & Wolfe, 1976). 47 and corotating interaction regions (CIRs) are solar wind stream structures that persists over 48 several solar rotations, leading to repeated occurrence of stream interactions such that they 49 co-rotate with the Sun (Balogh, Gosling, Jokipii, Kallenbach, & Kunow, 1999; Richardson, 50 2018). These transient solar events have severe impacts on the atmosphere and ionosphere 51 of Earth (e.g. B. T. Tsurutani et al. (2009)) as well as on unmagnetized planets, such as 52 increased atmospheric loss at Mars (e.g. Krishnaprasad, Thampi, and Bhardwaj (2019); 53 Lee et al. (2018); Thampi et al. (2018)). 54

The SEPs undergo changes in their properties, such as they accelerate at flare sites or at 55 interplanetary shocks upon traveling through the heliosphere (Pesses, Van Allen, Tsurutani, 56 & Smith, 1984; B. T. Tsurutani, Smith, Pyle, & Simpson, 1982). It is also observed that 57 the energetic particle increases in intensity-time profiles have well-defined forms dependent 58 on the location of the source relative to the observer and the presence and strength of 59 interplanetary shocks and shock normal angle (Cane, Reames, & von Rosenvinge, 1988; 60 Reames, 1995; B. T. Tsurutani & Lin, 1985; Van Hollebeke, Ma Sung, & McDonald, 1975). 61 The SEP events are broadly classified into 'gradual' and 'impulsive' based on the intensity 62 rise rate and duration, and particle compositions (Reames, 1995, 2013). Gradual SEP events 63 are dominated by high-energy protons (that is, large p/e ratios) with normal ion abundance 64 ratios and charge states, while impulsive SEP events are dominated by 0.1-100 keV electrons 65 (that is, small p/e ratios) with enhanced ³He (and heavier ion) emissions and charge states. 66

Parker (1958) suggested that interplanetary magnetic field (IMF) lines form an Archimedean 67 spiral in the solar equatorial plane, assuming the footpoints of the magnetic field lines are 68 fixed in the photosphere, which rotates with the Sun. An enhancement in SEP flux is ob-69 served at a vantage point either when the shock associated with a stream or ejection directly 70 passes the observer, or if the IMF is connected to the observer site (as the charged particles 71 can gyrate and move along the field lines, i.e. parallel transport from the source to the ob-72 server), or because of perpendicular transport by cross-field diffusion or drift (Zhang, Qin, 73 & Rassoul, 2009). The particles are generally accelerated in CME-driven shocks close to the 74 Sun ($\sim 3-10$ solar radii, i.e. within 1 AU), as well as beyond and are streamed out through 75 the heliosphere following magnetic field lines (Chollet et al., 2010). These gradual events are 76 observed over a wide longitude interval, unlike the impulsive events which are restricted to 77 $< 30^{\circ}$ longitude cone (Reames, 1995). The intensity peak near the shock is generally called 78 the energetic storm particle event. In large CME-related SEP events, changes in field line 79 connectivity of the spacecraft to different particle acceleration regions will result in changes 80 in intensity-time profiles. 81

Recently, Xie, Mkel, St.Cyr, and Gopalswamy (2017) studied three SEP events observed 82 in the solar cycle 23 by STEREO A, B, and near-Earth (L1) spacecraft with a wide lon-83 gitudinal distribution of particles. They examined whether the observations of SEPs from 84 different vantage points could be explained by acceleration and injection by the spatially 85 extended shocks or whether another mechanism such as cross-field transport is required, 86 and found that cross-field diffusion is the likely candidate for some of the enhancements 87 observed with wide longitudinal spread. Cross-field diffusion can result from interactions 88 between energetic protons and magnetic field magnitude decreases (da Costa Jr., Tsuru-89 tani, Alves, Echer, & Lakhina, 2013; B. T. Tsurutani & Thorne, 1982). The magnetically 90 connected SEP intensities are often found to be an order of magnitude lower than the SEPs 91 directly coming to the observer location (Xie et al., 2017). Simultaneous observations of 92 SEP events using a constellation of spacecraft, at different longitudes and radial positions, 93 may give us an idea of how the longitudinal spread of the SEP intensity varies, in addition 94 to other observables. 95

The SEP events of July 2017 are special in a sense that these are quite intense and 96 appeared in the deep descending-to-minimum phase of the historically weak solar cycle 24 97 (Liu, Zhao, Hu, Vourlidas, & Zhu, 2019; Luhmann et al., 2018; Paouris & Mavromichalaki, 98 2017). This is surprising, as we do not expect such intense energetic particle events in the aq declining and late phase of a solar cycle (during solar maximum, there are typically mainly 100 CMEs, whereas in the period of study during the decay phase, there are both CMEs and 101 SIRs). But such exceptional solar activity is not unprecedented and in fact the late solar 102 cycle 23 also had such SEP events (von Rosenvinge et al., 2009). There are a few studies 103 on the CMEs and associated energetic particle events of July 2017, and their space weather 104 impacts. The energetic particles associated with the 16 July 2017 Earth directed CME event 105 arrived with a delay at the Magnetospheric Multiscale Mission due to the magnetic connec-106 tivity of the satellite (Blake, Fennell, Turner, Cohen, & Mauk, 2019). There was a prompt 107 enhancement in Earth's radiation belt electron flux during the CME-shock compression and 108 subsequent geomagnetic storm, observed by the Relativistic Electron Proton Telescope in-109 strument on board Van Allen Probes (Patel, Li, Hudson, Claudepierre, & Wygant, 2019). 110 They used an MHD-test particle simulation to reproduce the observations. During the 24 111 July 2017 CME event, a multistep Forbush decrease with a remarkable total amplitude of 112 more than 15% was observed by Mars Science Laboratory/Radiation Assessment Detector 113 at Mars (Dumbović et al., 2019). 114

The combination of observations performed simultaneously by several spacecrafts located at various heliospheric locations is a tool to investigate the spatial distribution of SEP events. Using measurements from widely separated spacecrafts in longitude and radial distance in the inner heliosphere, we examine SEP proton intensity-time profiles present in the July 2017 events and discuss their attributes in the context of the Sun, state of the surrounding heliosphere, in situ plasma and magnetic field signatures, spacecraft's magnetic
 connectivity to the shock, and the spectral differences at these locations.

2 Data and Method

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The solar disk images are from the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA; https://sdo.gsfc.nasa.gov/) and Solar TErrestrial RElations Observatory Ahead (STEREO-A) Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) Extreme Ultraviolet Imager (EUVI; https://stereo-ssc.nascom.nasa .gov/). The white-light coronagraph images are from the Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO)-C2 and STEREO-A/SECCHI Coronagraph-2 (COR2).

The energetic proton observations from the first Sun–Earth Lagrange point (L1 at ~ 0.99 130 AU) are from the Low Energy Magnetic Spectrometer (LEMS) of Electron Proton Alpha 131 Monitor (EPAM) sensor onboard the Advanced Composition Explorer (ACE) spacecraft 132 (Gold et al., 1998). The ACE Solar Wind Electron Proton Alpha Monitor (SWEPAM) and 133 magnetic field experiment (MAG) measurements are used for IMF and solar wind speed 134 observations at 1 AU. The observations near Earth are from the Energetic Particle Sensor 135 (EPS) onboard Geostationary Operational Environmental Satellites (GOES-13), Geosta-136 tionary Radiation Spectrometer (GRASP) onboard Geostationary Satellite (GSAT-19), and 137 the Solid State Telescope (SST) onboard Acceleration Reconnection Turbulence and Electro-138 dynamics of the Moon's Interaction with the Sun (ARTEMIS) spacecraft. The STEREO-A 139 Solar Electron Proton Telescope (SEPT; Müller-Mellin et al. (2008)), Low Energy Telescope 140 (LET; Mewaldt et al. (2008)), and High Energy Telescope (HET; Richardson et al. (2014); 141 von Rosenvinge et al. (2008)) particle telescopes are also used for energetic proton observa-142 tions at 1 AU from a different heliospheric longitude with respect to near-Earth spacecraft. 143 The In-situ Measurements of Particles and CME Transients (IMPACT)/Magnetometer 144 (MAG) magnetic field and PLAsma and SupraThermal Ion Composition (PLASTIC) solar 145 wind plasma measurements are used for IMF and solar wind observations from STEREO-146 A. The GOES-13 differential and integral fluxes are taken from OMNIWeb data center 147 (https://omniweb.gsfc.nasa.gov/). The ACE data are obtained from ACE Science Cen-148 ter (http://www.srl.caltech.edu/ACE/ASC/) and the STEREO-A data are obtained from 149 STEREO Science Center (http://www.srl.caltech.edu/STEREO/). The ARTEMIS data 150 are obtained from http://artemis.ssl.berkeley.edu/. 151

GSAT-19 is an Indian communication satellite launched in June 2017 that carries GRASP payload to monitor and study the nature of charged particles and the influence of space radiation on satellites and their electronic components. The instrument measures the energy and flux of incident particles, and also enables particle identification by the E–dE technique. GSAT-19 is orbiting in 82°E longitude, while GOES-13 was at 75°W longitude of Earth. The in situ measurements from GRASP can provide additional data from geostationary orbit that can lead to improved models on space radiation.

The Solar Energetic Particle (SEP) instrument onboard Mars Atmosphere and Volatile 159 Evolution (MAVEN) spacecraft in orbit around Mars provides SEP proton and electron 160 observations near 1.5 AU (Larson et al., 2015). This instrument consists of two identical 161 sensors, SEP 1 and SEP 2, each consisting of a pair of double-ended solid-state telescopes 162 to measure 20 keV-200 keV electrons and 20 keV-6 MeV protons in four orthogonal view 163 directions that are positioned to adequately cover the canonical Parker spiral direction 164 around which SEP distributions are centered (Larson et al., 2015). The data used in this 165 study are the proton data in the form of energy fluxes measured by the SEP 1 sensor 166 in the forward and reverse looking fields of view (FOV). The proton counts measured by 167 SEP/MAVEN in the lower energy channels (< 100 keV) are also contributed by the O⁺ 168 pickup ions from Mars, and hence are removed from the analysis (Larson et al., 2015; 169 Rahmati et al., 2015). The upstream solar wind velocity from Solar Wind Ion Analyzer 170



Figure 1. CME eruption site near AR 12665 on the solar disk imaged by (a) SDO/AIA on 14 July, 01:40 UT and (b) STEREO-A/EUVI on 23 July, 04:15 UT.



Figure 2. (a) CME1 structure on 14 July, 02:24 UT by SOHO/LASCO C2 and (b) CME2 structure on 23 July, 05:24 UT by STEREO-A/COR2.

(SWIA) and IMF from Magnetometer (MAG) are obtained using the method given by 171 Halekas et al. (2017). The method is based on the measured solar wind bulk flow speed 172 (|v|), proton scalar temperature (T), altitude (R), and normalized magnetic field fluctuation 173 levels $(\sigma_B/|B|)$. Here, σ_B is the root-sum-squared value of the 32 Hz fluctuation levels in all 174 three magnetic field components over a 4 sec interval and |B| is the total magnetic field. To 175 select undisturbed solar wind intervals (in each orbit), points with |v| > 200 km/s, $\sigma_B/|B|$ 176 < 0.15, R > 500 km, and $\sqrt{T/|v|} < 0.012$ are chosen (Halekas et al., 2017). The MAVEN 177 data are obtained from the Planetary Data System (https://pds.nasa.gov/). 178

¹⁷⁹ During July 2017, both STEREO-A and Mars were located at the back side of the ¹⁸⁰ Sun as viewed from Earth. STEREO-A was at -132° HEE (Heliocentric Earth Ecliptic) ¹⁸¹ longitude, and Mars was at $\sim -178^{\circ}$ HEE longitude, with a longitudinal separation of $\sim 46^{\circ}$ ¹⁸² between STEREO-A and Mars (with Earth being at a reference heliolongitude of 0°). Mars ¹⁸³ was at a radial distance of 1.58 AU from the Sun, while STEREO-A was at ~ 0.96 AU during ¹⁸⁴ this period.

The Wang-Sheeley-Arge (WSA)-ENLIL+Cone model simulations (Mays et al., 2015; 185 Odstrcil, 2003) are taken from Community Coordinated Modeling Center (CCMC; https:// 186 ccmc.gsfc.nasa.gov/). This combined time-dependent model consists of solar coronal 187 model WSA coupled with the global heliospheric solar wind magnetohydrodynamic (MHD) 188 model ENLIL, and CMEs (spherical shaped high pressure gusts) inserted using Cone model-3D 189 CME kinematic and geometric parameters. The inputs to the model simulations shown in 190 Figures 1 and 2 (such as the National Solar Observatory (NSO) Global Oscillation Network 191 Group (GONG) Potential Field Source Surface (PFSS) synoptic magnetic field maps and 192 Cone model parameters) are described in Luhmann et al. (2018). The simulations gives a 193 global heliospheric context during the events, as well as the relative planetary and spacecraft 194 positions. The simulated solar wind velocities appear to capture the ACE and STEREO-195 A observed velocities, thus giving confidence on the wider inner heliospheric simulations 196 (Luhmann et al., 2018). 197

¹⁹⁸ **3** Observations

There were two major CME eruptions during July 2017. The NOAA Active Region 199 (AR) 12665 (located around source coordinate S07W44 (652", -165")) was the prominent 200 eruptive region on the Sun during this period (Luhmann et al., 2018). The SDO Helioseismic 201 and Magnetic Imager (HMI) showed the presence of a dark sunspot associated with AR 202 12665. The main eruptions for the period were multiple, with fast and wide ejections following one another by roughly a week with the CME ejecta headed first to the west of 204 Earth and then later in the general direction of STEREO-A and Mars (Luhmann et al., 205 2018). Figure 1a shows the SDO/AIA image of the solar disk at 193 Å, and Figure 1b 206 shows the STEREO-A EUVI image of the solar disk at 195 Å. Both images indicate the 207 presence of eruption site near the active region, as well as the presence of CME loops. 208

Figure 2 shows the CME structures observed by the white-light coronagraphs onboard 209 SOHO and STEREO-A during the two major interplanetary CME events of July. The 210 SOHO/LASCO C2 coronagraph image (Figure 2a) and STEREO-A/COR2 coronagraph 211 image (Figure 2b) show the CME eruptions. The CME on 14 July (hereafter CME1) first 212 appeared in LASCO-C2 at 01:25 UT and in LASCO-C3 at 02:18 UT, which is consistent 213 with their FOV and an initial CME linear speed of $\sim 1200 \text{ km sec}^{-1}$ (https://cdaw.gsfc 214 .nasa.gov/CME_list/). The CME on 23 July (hereafter CME2) first appeared in STEREO-215 A COR-2 at 04:54 UT (http://spaceweather.gmu.edu/seeds/secchi.php). The CME1 216 had an associated C-class flare and a long-duration ($\sim 116 \text{ min.}$) M2.4-class flare originated 217 from AR 12665, while the CME2 had two associated B-class flares originated from the same 218 active region (Dumbović et al., 2019). 219



Figure 3. The snapshots of WSA-ENLIL+Cone model simulations of inner heliospheric conditions such as solar wind radial velocity (color contour) and IMF lines (black and white lines) during (a) 14 to 20 July 2017 event at Earth (CME1 event) and (b) 23 to 28 July 2017 event at STEREO-A and Mars (CME2 event).

Figure 3 shows the snapshots of WSA-ENLIL+Cone model (hereafter ENLIL) simu-220 lations of inner heliospheric conditions such as solar wind radial velocity and IMF lines 221 during 14 to 20 July 2017 event at Earth (CME1; Figure 3a) and 23 to 28 July 2017 event 222 at STEREO-A and Mars (CME2; Figure 3b). The event period ENLIL simulation results 223 for July are described in detail by Luhmann et al. (2018). The July 2017 events seemed 224 to arise in conjunction with the appearance of a coronal pseudostreamer (Luhmann et al., 225 2018). The simulations show the magnetic field lines during the event period, and some of 226 which connects between the spacecraft and the CME from inside as well as from outside 227 the spacecraft heliocentric radius. Luhmann et al. (2018) calculated the shock connection 228 radius, which shows that Earth is connected to shocks from outside 1 AU during the CME2 229 event. 230

Figure 4 shows the solar wind proton velocity, temperature, and magnetic field obser-231 vations by ACE and STEREO-A, during the two CME events and a SIR event in July 2017. 232 The shock arrival is identified based on the discontinuities/jumps in the plasma and field 233 observations. The shocks in the STEREO-A plasma and magnetic field data are identified in 234 the STEREO-A interplanetary shock list (https://stereo-ssc.nascom.nasa.gov/data/ 235 ins_data/impact/level3/STEREO_Level3_Shock.pdf). The forward and reverse shocks in 236 STEREO Level 3 shocks list are identified using 8 sec⁻¹ magnetic field data, which is rotated into shock normal coordinates to examine the existence of associated shock waves and field 238 changes consistent with the Rankine-Hugoniot relations (Jian et al., 2013; B. Tsurutani et 239 al., 2011). At forward shocks, solar wind speed, proton temperature, and magnetic field 240 increase simultaneously, whereas at reverse shocks, solar wind speed increases, while proton 241 temperature, and magnetic field decrease (Jian et al., 2013). Shocks and their sheaths are 242 not part of CMEs, and CME shocks only exist for fast CMEs and first form when the speed 243



Figure 4. (a) The 16 July CME1-shock arrival observed by ACE, (b) The 16 July SIR-shock arrival observed by STEREO-A, and (c) The 24 July CME2-shock arrival observed by STEREO-A.

of the CME is faster than the local magnetosonic speed (Tsurutani, B., Wu, S. T., Zhang, 244 T. X., & Dryer, M., 2003). This occurs somewhere between 5 and 10 solar radii depending 245 on the local plasma conditions. Slow (submagnetosonic) CMEs do not form shocks and 246 therefore do not accelerate energetic particles (B. Tsurutani, Gonzalez, Zhou, Lepping, & 247 Bothmer, 2004). Although not all shocks have clear signatures in plasma properties, the 248 two fast CME events and the SIR event described here has clear plasma and magnetic field 249 signatures of forward shock (FS) arrivals (Figure 4). The CME1 shock arrives at L1 on 16 250 July, 05:16 UT (Figure 4a), SIR shock arrives at STEREO-A on 16 July, 19:39 UT (Figure 251 4b), and CME2 shock arrives at STEREO-A on 24 July, 14:36 UT (Figure 4c). The shock 252 arrivals at Mars location is not shown since we do not have high time resolution and con-253 tinuous upstream solar wind and IMF data from the MAVEN spacecraft (as the orbit of 254 MAVEN is elliptical with nominal periapsis around 150-160 km, and the spacecraft watching 255 the "pure" solar wind only during a segment of the orbit as described earlier). 256

The CME1 event observed at L1 point by ACE spacecraft and at Earth's geostationary 257 orbit by GOES and GSAT-19 satellites was due to an Earth directed CME. Figure 5a shows 258 the IMF and solar wind velocity observed by ACE during 12 to 31 July 2017. A fluctuating 259 IMF with increase in total |B| to ~ 25 nT and an increase in solar wind speed to 664 km 260 sec^{-1} was observed. Figure 5b shows the SEP intensity-time profiles of energetic protons in 261 different energy channels (between $\sim 100 \text{ keV}$ and 4.75 MeV) observed by EPAM/ACE. The 262 energetic proton intensities increase gradually from 14 July up to 20 July, with a crescendo observed on 16 July. The peak flux during this period in the lowest energy channel (110 keV 264 to 190 keV) was 3×10^5 pfu MeV⁻¹ (here the particle flux unit, 1 pfu = 1 particle cm⁻² s⁻¹ 265 sr^{-1}). The sudden spikes in the intensity profiles, such as those seen on 22 July are due to 266 the accelerated ions propagating from the Earth's bow shock (Bruno, Christian, de Nolfo, Richardson, & Ryan, 2019). The event was also observed by GOES and GSAT-19. The 268 proton flux enhancement can be seen from 14 to 16 July with a peak enhancement of 12 pfu in 269 GOES >10 MeV channel and 7 pfu in GSAT-19/GRASP 5-85 MeV channel (Figure 5c). The 270 GRASP data are being used for the first time, and therefore the comparison of GRASP with 271 GOES also serves as a validation for GRASP observations. The enhancement seen at GOES 272 and GSAT is before the peak flux observed at ACE. This is because the GOES and GSAT 273 detected protons are of higher energies, which travel faster than the comparatively low-274 energy SEPs observed by ACE. The combination of ACE (lower energy) and GOES/GRASP 275 (higher energy) shows population evolution by velocity dispersion, where the most energetic 276 protons arrive first, ~a day before the CME plasma and field disturbance. This event 277 was also observed by the solid state telescopes onboard ARTEMIS P1 and P2 (the former 278 THEMIS b and c satellites) in orbit around Moon. The observed intensity-time profiles of 279 100 keV to 6 MeV energetic protons are similar to the ACE observations (not illustrated). 280 Hence, the observations from ACE and ARTEMIS provide independent measurements of 281 the same events at similar energies, and it is important to note that these particles are 282 observed near the Lunar orbit as well. The CME1 event caused a geomagnetic storm with 283 disturbance storm time index, Dst_{min} of -72 nT observed on 16 July ${\sim}15$ UT. 284

The CME2 (second major event of July), starting from 23 July and lasting up to 28 285 July is primarily due to a Mars directed CME, which was observed by both STEREO-A 286 and MAVEN. Figure 6a shows the IMF and solar wind velocity observed by STEREO-A 287 during 12 to 31 July 2017. The peak total magnetic field was 58 nT (on 24 July) and peak 288 solar wind speed was 818 km sec⁻¹ (on 25 July). Figure 6b shows the SEP intensity-time 289 profiles of energetic protons of energy between 100 keV and 100 MeV in different channels. 290 The maximum enhancement seen in the lowest energy channel (100 keV to 190 keV) was 291 $>10^7$ pfu MeV⁻¹ on 24 July. The different energy channels shown in Figure 6b are from 292 SEPT (~ 100 keV to 2.2 MeV), LET (4 to 12 MeV), and HET (>13 to 100 MeV) particle 293 detectors onboard STEREO-A. A dip in intensity profile is observed in all these energies on 294 25 July. 295



Figure 5. (a) The near Earth observations of IMF (|B|, B_x , B_y , B_z) and solar wind speed during 12–31 July 2017, (b) ACE observations of SEP proton intensity–time profiles during 12–31 July 2017, and (c) GOES and GRASP observations of SEP proton intensity–time profiles (GOES: differential fluxes and >10 MeV integral flux, GRASP: 5–85 MeV integral flux) during 12–31 July 2017.



Figure 6. (a) The STEREO-A observations of IMF (|B|, B_x , B_y , B_z) and solar wind speed during 12–31 July 2017 and (b) STEREO-A (SEPT, LET, HET telescopes) observations of SEP proton intensity–time profiles during 12–31 July 2017. The white gap on 22 July is due to absence of data.

The CME2 event was also observed by MAVEN in orbit around Mars. Figure 7a shows 296 the upstream solar wind velocity and magnetic field measurements from MAVEN spacecraft. 297 Figure 7b shows the energy-time spectrogram of differential energy flux of protons from 12 298 to 31 July observed by the forward facing sensor one (1F) of SEP instrument onboard 299 MAVEN. An enhancement in SEP proton flux is observed between 23 and 28 July 2017. 300 Figure 7c shows the intensity-time profiles of protons in different energy channels between 301 100 keV and 5.11 MeV by forward looking sensor (1F) and Figure 7d shows the observations 302 by reverse looking sensor (1R). A peak flux of 2×10^5 pfu MeV⁻¹ was observed on 26 July 303 in the 100 keV to 200 keV energy channel. The data just prior to the peak of proton 304 flux enhancement are removed because of electron contamination to the proton channels, 305 in the vicinity of peak electron flux (Luhmann et al., 2018). The reverse facing data are 306 also shown, because the pick-up oxygen ions predominantly appear in the forward facing 307 MAVEN/SEP detectors and hardly appear in the reverse facing detectors, and therefore 308 confirms the presence of SEP related enhancements (Larson et al., 2015). 309

Two SIR events are also identified from the solar wind and magnetic field data and STEREO IMPACT Level 3 SIR events list (https://stereo-ssc.nascom.nasa.gov/data/ ins_data/impact/level3/STEREO_Level3_SIR.pdf). One from 16 to 18 July (with a maximum solar wind speed of 493 km sec⁻¹ and magnetic field intensity of 12.5 nT) and another one from 19 to 21 July (with a maximum solar wind speed of 572 km sec⁻¹ and magnetic field intensity of 10.2 nT). As mentioned earlier, the former (16 July SIR) had a shock associated it (Figure 4b) with higher SEP proton intensities (Figure 6b).

Interestingly, energetic proton enhancement is also observed (at Earth) when the CME2 317 was not directly passing the observer, and when the observer is on the opposite side of the 318 Sun as viewed from the CME2 longitude. Energetic proton enhancements can be seen in 319 ACE profiles (28-30 July, Figure 5b), as well as in GOES lower energy channels such as 320 4.2 to 8.7 MeV (Figure 5c). This is during the period when the CME2 energetic proton 321 event impacted STEREO-A and MAVEN, those two spacecraft were located in western 322 heliospheric longitudes. This SEP proton enhancement observed at Earth's location is due 323 to magnetic connections to distant shocks, that is shocks beyond heliocentric radius of 324 the observer (Figure 5a of Luhmann et al. (2018)). The SEPMOD calculations based on 325 the ENLIL simulation results for similar proton energy range are capturing the smaller 326 enhancements during 28-30 July (Luhmann et al., 2018). We can also see that bulk solar 327 wind speed and IMF do not show any significant enhancement during 27 to 31 July when 328 the SEP proton enhancement is observed at the ACE location. However the solar wind 329 speed is relatively higher for a period prior to the SEP proton enhancement from 21 to 26 330 July (Figure 5a), this could be due to the passage of a high speed stream during this period 331 as observed from the ENLIL simulation shown in Figure 3b. 332

Figure 8a shows the power-law fits for SEP proton energy spectra during July 2017 events observed by ACE. The energy spectra are fitted with a power-law of the form $AE^{-\gamma}$. Two distinct SEP proton enhancements were detected by ACE from 14 to 20 July, associated with the CME1 eruption. The event averaged spectrum of the two SEP events are shown in red (14/07, 18:14 UT to 17/07, 00:43 UT) and brown (17/07, 15:50 UT to 20/07, 18:57 UT) colors. The event averaged spectrum of the SEP proton enhancement due to shock connectivity is shown in magenta color (27/07, 21:22 UT to 30/07, 15:50 UT).

Figure 8b shows the STEREO-A and MAVEN observed event averaged energy spec-340 tra during the SEP proton events of July 2017. There were two distinct SEP proton en-341 hancements from 23 to 27 July, associated with the CME2 eruption. The spectra of these 342 individual SEP events are shown in red (23/07, 10.48 UT to 25/07, 03.07 UT) and brown 343 (25/07, 05:31 UT to 27/07, 23:16 UT) colors. The energy spectra are fitted with a double 344 power law (with indices denoted as γ_a and γ_b) characterized by a spectral break at few tens 345 of MeV. The spectral transition (or break) is observed between 6 and 10 MeV energy. A 346 double power law or a power law with exponential rollover at a few to tens of MeV has 347 been reported in many events (e.g. Zhao, Zhang, and Rassoul (2016)). The event averaged 348



Figure 7. (a) MAVEN (near Mars) upstream observations of the IMF (|B|) and solar wind speed during 12–31 July 2017, (b) MAVEN observations of the SEP proton energy–time spectrogram of differential energy flux during 12–31 July 2017, (c) MAVEN observations of the SEP proton intensity–time profiles in the forward facing FOV of SEP 1 sensor during 12–31 July 2017, and (d) MAVEN observations of the SEP proton intensity–time profiles in the reverse facing FOV of SEP 1 sensor during 12–31 July 2017. The white gap before 22 July is due to low flux of particles, while after 22 July is due to poor quality of data.



Figure 8. Power-law fits for (a) ACE, (b) STEREO-A and MAVEN observations of SEP proton events during July 2017. The left panel shows ACE observations during SEP periods from 14 to 17 July (red), 17 to 20 July (brown). The shock connected event from 27 to 30 July (magenta) is also shown. The right panel shows STEREO-A observations during SEP periods from 23 to 25 July (red), 25 to 27 July (brown). The SEP proton enhancements due to SIR event at STEREO-A (blue stars, 17 to 18 July) and MAVEN (blue circles, 14 to 17 July) are also shown - extrapolated to higher energies. The spectral indices and the uncertainties of the spectral index estimate are also indicated.

energy spectra of the CME event observed by MAVEN is not shown here due to the electron contamination to the proton channels.

The blue color fits shows the event averaged energy spectra for the SIR event observed 351 by STEREO-A at ~ 0.96 AU (17/07, 00:00 UT to 18/07, 09:50 UT) and MAVEN at ~ 1.58 352 AU (14/07, 18:00 UT to 17/07, 13:12 UT). As mentioned earlier, the longitudinal separation 353 between MAVEN and STEREO-A was about 46° , with the stream arriving at MAVEN 354 before STEREO-A. The energy spectrum observed by MAVEN as well as that observed by 355 STEREO-A are single power laws (with an index denoted as γ_a) in the energy range up to 356 ~ 2 MeV for STEREO-A, and upto ~ 1 MeV for MAVEN. These are the energy ranges where 357 we have observed particle fluxes above the background levels, at both these locations. The 358 spectra are extrapolated to higher energies ($\sim 40 \text{ MeV}$) in order to asses the differences in 359 high energy fluxes at these two locations. We can see that the high energy proton flux is 360 higher at Mars in comparison to the flux at 1 AU (Figure 8b). 361

The spectral analysis shows that the STEREO-A and Mars directed SEP events as-362 sociated with the interplanetary CME2 are stronger (spectral indices of 1.3 and 1.4) than 363 the Earth directed SEP events associated with the interplanetary CME1 (indices of 1.6 and 2.2). Also, the peak intensities are higher by around an order of magnitude for the CME2 365 event. The SEP event due to shock connectivity observed at Earth between 28 and 30 July 366 is having a spectral index of 1.4 which is similar to the index of the 25 to 27 July event 367 directly seen by STEREO-A. An onset delay of ~ 2 days is observed for the shock connected 368 event, which is due to the separation between the CME2 shock and the observer location at 369 L1/Earth. 370

The 16 July SIR event observed at MAVEN and STEREO-A is having spectral indices of 1.6 and 2.6 respectively. Enhanced particle intensities by a factor of 6 (for 1 MeV protons) are observed at Mars, also the event spectrum is harder, indicating acceleration of energetic protons during the radial propagation of ~0.62 AU. The energy spectra are extrapolated to higher energies, which shows higher proton fluxes at higher energies at Mars in comparison to 1 AU. This is important in the context of space weather, since energies of several MeV are required to degrade solar arrays, whilst energies above 40 MeV are required to disrupt electronic systems within a spacecraft.

379 4 Discussion

The onset time of the CME event at a location can be calculated using Velocity Dispersion Analysis (VDA), which is based on the assumptions that the first particles observed at a given distance from the Sun have been released simultaneously, propagate the same path length, and experience no scattering or energy changes (Laitinen, Huttunen-Heikinmaa, Valtonen, & Dalla, 2015). According to this, the CME event onset time,

 $t_{onset}(v) = t_{injection} + (s/v) ,$

where $t_{injection}$ is the particles' injection time at the source, s is the traveled distance, 385 and v is the particle velocity. The injection of particles starts during the CME eruption 386 from the Sun. For the CME1 event (Earth directed), eruption starts at $\sim 01:25$ UT on 14 387 July (Figure 2a, https://cdaw.gsfc.nasa.gov/CME_list/), the particles with a speed of 388 664 km sec⁻¹ will arrive at 0.99 AU [ACE location] in \sim 62 hours. For the CME2 event 389 (STEREO-A and Mars directed), the eruption starts at ~04:54 UT on 23 July (Figure 2b, 390 http://spaceweather.gmu.edu/seeds/secchi.php), the CME with a speed of 811 km 391 sec^{-1} will arrive at 0.96 AU [STEREO-A location] in ~49 hours, while the CME will arrive 392 at 1.58 AU [MAVEN location] in \sim 81 hours. These calculations of event arrival times are 393 matching with the observations of CME arrival at ACE (Figure 5), STEREO-A and Mars 394 (Figures 6 and 7). 395

The context and space weather impacts of September 2017 solar events are extensively 396 studied for Earth as well as for Mars (Chertok, Belov, & Abunin, 2018; Jiggens et al., 2019; 397 Lee et al., 2018; Liu, Zhu, & Zhao, 2019; Perez-Peraza, Mrquez-Adame, Caballero-Lopez, 398 & Manzano Islas, 2020). The active region responsible for the major flares and CMEs of 399 September 2017 was AR 12673 (located at S09W91), while that of July 2017 was AR 12665 400 (located at S07W44). A southern high-latitude coronal hole was responsible for the high 401 speed streams of July, while a southern mid-latitude coronal hole was responsible for the 402 high speed streams of September. The events in July and September have comparable 403 peak particle fluxes (Bruno et al., 2019; Luhmann et al., 2018). The ICME/SIR-driven interplanetary shocks of September had unusually high magnetosonic Mach numbers (Hajra, 405 Tsurutani, & Lakhina, 2020). The angle of propagation (θ_{Bn}) of the September ICME-406 driven FSs varied from $\sim 19^{\circ}$ to $\sim 90^{\circ}$ relative to the ambient IMF directions, while their 407 strengths varied from Mach ~ 4.0 to ~ 6.7 (Hajra et al., 2020). The STEREO-A observed 408 ICME-driven FSs of July had a Mach number from ~ 2.0 to ~ 2.4 . The θ_{Bn} of the September 409 SIR-driven FSs varied from $\sim 9^{\circ}$ to $\sim 84^{\circ}$ relative to the ambient IMF directions, while their 410 strengths varied from Mach ~ 1.7 to ~ 4.3 (Hajra et al., 2020). The STEREO-A observed 411 SIR-driven FS of July had a Mach number ~1.42 (https://stereo-ssc.nascom.nasa.gov/ 412 data/ins_data/impact/level3/). 413

Both July and September solar and SEP events had similar characteristics due to similar 414 source region and eruptions (Luhmann et al., 2018). The spectral indices of the 4, 6, and 415 10 September SEP proton events are 0.5, 1.3, and 1.2 respectively for ACE observations 416 (Bruno et al., 2019). While the spectral indices of 14 to 20 July events are 1.6 and 2.2 417 (Figure 8a). The spectral indices of the 4, 10, and 17 September SEP proton events are 418 0.2, 1.2, and 1.2 respectively for STEREO-A observations (Bruno et al., 2019). While the 419 spectral indices of 23 to 27 July events are 1.3 and 1.4 (Figure 8b). Thus the Earth directed 420 events of July was softer compared to the Earth directed events of September, while the 421 STEREO-A directed events of July and September are of similar spectral characteristics. 422 Three successive CMEs that erupted from AR 12673 during early September 2017 resulted 423 in an intense two-step geomagnetic storm (main dip Dst_{min} of -142 nT and a secondary dip 424

⁴²⁵ Dst_{min} of -124 nT) driven by the interplanetary CME–CME interactions occurring among ⁴²⁶ the eruptions involved (Scolini et al., 2020). The 16 July CME1 event caused a geomagnetic ⁴²⁷ storm with Dst_{min} of -72 nT, which is a smaller storm compared to the two events of ⁴²⁸ September.

As mentioned earlier, for the SIR event observations at STEREO-A and Mars, enhanced 429 proton intensities are observed by MAVEN. The spectral index observed by MAVEN is 430 ~ 1.6 , which is lower than the spectral index observed by STEREO-A, which is ~ 2.6 (Figure 431 8b). Thus the event averaged spectrum is more harder at Mars, indicating acceleration of 432 energetic protons during the radial propagation of ~ 0.62 AU. One possibility for the observed 433 hardened spectra is that the Parker spiral is more tightly wound at larger heliocentric 434 distances, this would make the SIR shock more quasiperpendicular (Pesses et al., 1984). 435 These spectral index estimates of SIR-accelerated SEP enhancements are in agreement with 436 the previous study by M. I. Desai et al. (1999), where they have shown the energy spectra 437 of 50 keV to 20 MeV protons accelerated at SIRs at Ulysses spacecraft. If we consider the 438 general Fisk and Lee (1980) model, it can be seen that the distribution function rolls over 439 above ~ 1 MeV energy. However, we do not see this rollover. As mentioned earlier, we do not 440 have data points beyond ~ 2 MeV (near 1 AU) and ~ 1 MeV near (1.5 AU) to determine the 441 exact rollover energy. Similar to this, proton flux enhancements near 1.5 AU associated with 442 SIR event of June 2015 is previously reported by Thampi, Krishnaprasad, Shreedevi, Pant, 443 and Bhardwaj (2019). The observations of SEP proton events during CMEs suggests that 444 shock acceleration takes place within 1 AU itself during CME events (Thampi et al., 2019). 445 The observations of SIR related SEP proton enhancements observed near Mars compared 446 to 1 AU are important in this context because of the addition of a vantage point at 1.5 AU, 447 and as such observations were previously sparse between 1 and 3 AU. 448

Helios 1 and 2 spacecraft has a long term observation of SIRs in the inner heliosphere 449 between ~ 0.3 AU and 1 AU. There are extensive observations of heliospheric conditions at 450 1 AU since the arrival of solar monitors at L1 point. The first detailed observations of SIRs 451 beyond the orbit of Earth were made by the Pioneer 10 and 11 spacecraft, and the three 452 dimensional aspect (that is, beyond the ecliptic plane) was given by Ulysses spacecraft 453 (Balogh et al., 1999). SIR boundaries tend to steepen to form a fast forward shock at 454 the leading edge of the interaction region and a sunward propagating reverse shock at the 455 trailing edge of the interaction region (Richardson, 2018). Pioneer 10 and 11 observations 456 suggests that such shocks form beyond 2 AU distances (Gosling, Hundhausen, & Bame, 457 1976; Hundhausen & Gosling, 1976; Smith & Wolfe, 1976). The present study suggests that 458 strong SIR-forward shock can form even at distances like ~ 1.5 AU. This could be due to the 459 the steeping of the leading edge of the interaction region at farther distances (Hundhausen & 460 Gosling, 1976). Also, as the stream expands at larger distances, the peak speeds are reduced 461 and the stream would become less structured as compared to 1 AU. Intensity variation of 462 0.9-2.2 MeV protons measured by the Helios, Pioneer 10/11 and near-Earth spacecraft in 463 several corotating particle events were obtained by Van Hollebeke, McDonald, Trainor, and 464 Rosenvinge (1978), which shows that the peak intensities in corotating particle events occur at a few AU. The observations from ~ 1.5 AU by MAVEN suggests that enhancement in 466 particle intensities can happen even from 1.5 AU. 467

SEPs are one of the main sources of particle radiation seen in space (Jiggens et al., 2019). 468 469 thus posing a major radiation risk for spacecraft systems and to astronauts in space. The transport of energetic protons through magnetically connected "roads" to diverse locations 470 in space thus cause unexpected radiation exposure to humans in the interplanetary space, 471 which is especially important in the context of human spaceflight. The lower spectral index 472 measured by MAVEN during the SIR event at Mars suggests that SIR-generated protons 473 may have harder spectra at Mars than at Earth. This is an important point for anyone 474 assessing the radiation risk for future human exploration of Mars. It raises the question 475 of whether there are features in space radiation environment that are more dangerous at 476 Mars than at Earth, i.e. features where the fluxes of higher energy protons (many MeV) 477

are greater at Mars. The results from the present study suggest that this may be the case for SIR-generated protons.

480 5 Summary

The solar events of July 2017 are studied using observations from multiple spacecraft near Earth, near Mars, and STEREO-A. The three heliolongitude observations, along with the radial gradient between Earth and Mars provides an opportunity to study both longitudinal and radial variation of SEPs propagating in the inner heliosphere. The STEREO-A was ~125° separated from Earth, while Mars had an angular separation of ~175° with respect to Earth. The widespread observations of energetic protons was associated with activity originated at NOAA AR 12665 located at the source coordinate S07W44 on the Sun.

There were two major interplanetary CME events and a SIR event during July 2017. 489 These solar activities are particularly interesting because they have occurred during the 490 late decay phase of the solar cycle 24. The 16 July CME1 was directed west of Earth and 491 the 24 July CME2 was in the general direction of STEREO-A and Mars. Earth and Mars 492 were on the opposite sides of the solar disk, while Mars and STEREO-A were aligned with 493 respect to the nominal Parker field. The CME2 event had higher plasma velocities and 494 around an order of magnitude higher SEP proton flux compared to the 16 July event, also 495 the event was wider $(>120^{\circ})$ in heliolongitude. The CME2 shock had magnetic connectivity 496 to Earth's location, which produced an SEP proton event at L1/Earth from 28 to 30 July 497 (Luhmann et al., 2018). An onset delay of ~ 2 days is observed for the event arrival at ACE 498 location. The spectral indices of the SEP proton event observed directly at STEREO-A and at the remote location of ACE was found to be similar (~ 1.4). The 16 July SIR event was 500 observed by both MAVEN and STEREO-A. Higher particle intensities by a factor of 6 for 501 1 MeV protons, and spectral hardening from 2.6 to 1.6 are observed at 1.58 AU, indicating 502 an acceleration of energetic protons in SIR forward shock during the radial propagation 503 of 0.62 AU in the interplanetary space. The observations of hardened spectra at 1.58 AU 504 compared to 0.96 AU could be due to the fact that Parker spiral is more tightly wound at 505 larger heliocentric distances, making the SIR shock more quasi-perpendicular. 506

⁵⁰⁷ Thus, the following major inferences are drawn from the study,

a) An energetic proton enhancement event was observed at 1 AU due to magnetic connectivity with a distant CME-driven shock, and the spectral index was found to be invariant with the source location. That is, the power-law spectral index of the SEP proton energy spectra remained the same at the source location as well as at a location which is magnetically connected.

b) The SIR forward shock of 16 July 2017 found to accelerate energetic protons between 0.96 AU and 1.58 AU. The comparison of energy spectra at these two vantage points shows that the spectra hardens as the energetic protons accelerates. One possibility is that the Parker spiral is more tightly wound at larger heliocentric distances. This would make the shock more steep. This is an important aspect considering the radiation risk during the human exploration to Mars.

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- .edu/ACE/ASC/). The STEREO-A IMPACT/PLASTIC data are taken from STEREO Sci-
- ence Center at http://www.srl.caltech.edu/STEREO/. The SDO AIA images are from
- https://sdo.gsfc.nasa.gov/. The STEREO-A/SECCHI EUVI and COR2 images are

⁵²³ SWEPAM/MAG data are taken from the ACE Science Center (http://www.srl.caltech

from STEREO Science Center at https://stereo-ssc.nascom.nasa.gov/. The SOHO 527 LASCO images are from https://soho.nascom.nasa.gov/. The GOES SEP flux data 528 are obtained from the SPDF OMNIWeb data center (https://omniweb.gsfc.nasa.gov/). 529 We thank the staff of the ACE and STEREO Science Centers for providing the ACE and 530 STEREO data and OMNIWeb team for providing the GOES data. The WSA-ENLIL+Cone 531 model simulations are provided by CCMC through their public Runs on Request system 532 (https://ccmc.gsfc.nasa.gov/; run number: Leila_Mays_080917_SH_1). We thank M. L. 533 Mays, CCMC, NASA GSFC for their openly available simulation runs. C. Krishnaprasad 534 acknowledges the financial assistance provided by ISRO through a research fellowship. This 535 research has made use of SunPy v1.1, an open-source and free community-developed solar 536 data analysis Python package (https://sunpy.org/). 537

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