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Special Section:
Impact of the Sept. 10, 2017, Solar Event on Mars

Key Points:
- IMA background counts provide the longest available record of penetrating energetic particles at Mars, covering more than a solar cycle
- Comparison with MAVEN/SEP shows IMA to be sensitive to >1 MeV electrons and >20 MeV protons, with good correlation ($\rho = 0.85$)
- Distribution of IMA data shows the September 2017 event to be the fourth strongest SEP event observed by Mars Express (2004–2018)

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The September 2017 SEP Event in Context With the Current Solar Cycle: Mars Express ASPERA-3/IMA and MAVEN/SEP Observations

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Abstract We use Mars Atmosphere and Volatile Evolution/Solar Energetic Particle (MAVEN/SEP) data to estimate the ranges of particle energies that generate background noise in the Analyzer of Space Plasmas and Energetic Atoms-3/Ion Mass Analyzer (IMA) instrument on Mars Express. The particles that generate IMA background counts are estimated to be electrons with energies >1 MeV and protons >20 MeV. The September 2017 event at Mars resulted in the strongest flux of energetic particles measured by MAVEN/SEP. We correspondingly use the IMA background data to compare this event with the rest of the last solar cycle and back to 2004, finding the event to be the fourth strongest solar energetic particle event detected by Mars Express.

Plain Language Summary The September 2017 event produced the strongest radiation flux measured at Mars by the Mars Atmosphere and Volatile Evolution (MAVEN) mission since late 2014. Such events may not only have effects on the evolution of the atmosphere but also pose a problem for equipment and future human presence. In order to understand how unusual events such as the September 2017 event are at Mars, we use MAVEN data to estimate the sensitivity to radiation of instruments on the older Mars Express (2004-) spacecraft. We find the September 2017 event to be the fourth strongest radiation event observed by Mars Express.

1. Introduction

Energetic particles, i.e., ions and electrons with energies above several tens of keV and generally up to a few GeV, permeate the solar system. Extrasolar sources generate galactic cosmic rays which constitute a near-constant energetic particle background. Far more variable are fluxes of particles produced near the Sun, i.e., solar energetic particles (SEPs). The strongest SEP fluxes are produced by solar flares and first-order Fermi acceleration at the shock boundaries of fast coronal mass ejections (CMEs) that propagate through and pile up the slower solar wind in their paths. While the induced magnetospheres of nonmagnetized planets like Mars efficiently screen the bulk of the planetary ionospheres from the energy carried by the solar wind (Ramstad et al., 2017), SEPs penetrate the induced magnetic barrier and precipitate into the planetary atmospheres, driving heating, dissociation, and ionization rates. The bursts of intense penetrating radiation poses operational hazards to equipment and potential future human presence at Mars.

A few instruments have been designed to measure energetic particle fluxes near Mars; however, no instrument has provided a long-term record of the SEP environment. The Solar Low Energy Detector instrument on the short-lived 1989 Phobos-2 mission only delivered data for ~2 months (McKenna-Lawlor et al., 1993). The Mars Radiation Environment Experiment (MARIE) is installed on the still operational Mars Odyssey (2001–) orbiter (Zeitlin et al., 2004); however, MARIE ceased to function in October 2003. Lately, the SEP investigation on the Mars Atmosphere and Volatile Evolution (MAVEN) mission has provided detailed measurements of the near-Mars energetic particle environment (Larson et al., 2015; Lillis et al., 2016); however, MAVEN has currently only been in operation at Mars for about 3.5 years.

The Mars Express (MEX) orbiter (2003–) carries the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) particles package, which includes the Ion Mass Analyzer (IMA) and Electron Spectrometer instruments

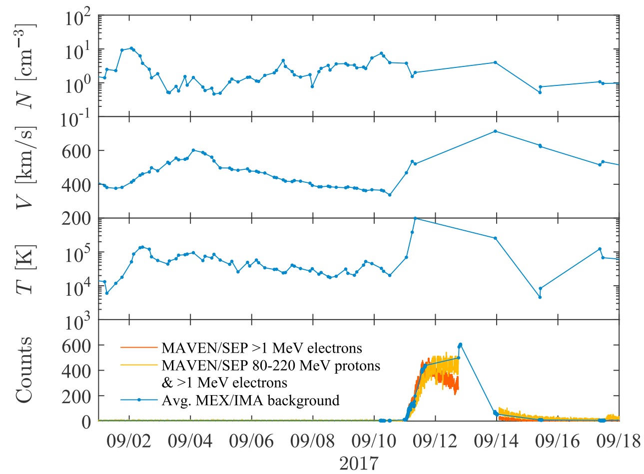

Figure 1. Solar wind moments (density, speed, and temperature) measured by Mars Express ASPERA-3/IMA (Ramstad et al., 2015). (bottom panel) Energetic particles measured by the MAVEN/SEP investigation for different energies and types of particles, as well as average IMA background counts. The time period is leading up to and including the September 2017 event. Note that the large intervals between MEX measurements are mainly due to limited operational time of ASPERA-3, an effect of power conservation efforts for MEX during the 2017 eclipse season. The gap in MAVEN/SEP data excludes a period when the instrument attenuator was active. ASPERA = Analyzer of Space Plasmas and Energetic Atoms; IMA = Ion Mass Analyzer; MAVEN/SEP = Mars Atmosphere and Volatile Evolution/Solar Energetic Particle; MEX = Mars Express.

(Barabash et al., 2006). The top hat electrostatic energy analyzers (ESAs) of IMA and Electron Spectrometer are only designed to measure ion and electron distributions up to 36 keV and 20 keV, respectively. However, sufficiently energetic particles can penetrate the walls and internal structure of the instruments and register as background counts on the microchannel plates (Futaana et al., 2008). The simultaneous presence of MEX and MAVEN at Mars since late 2014 presents an opportunity to estimate the IMA background energy sensitivity range and thus provide a long-term record of the SEP environment from 2004 to the present.

The Electron Reflectometer (ER) instrument on the Mars Global Surveyor (MGS, 1996–2006) orbiter also recorded spurious counts from penetrating energetic particles. Delory et al. (2012) estimated that MGS/ER was sensitive to >30 MeV particles, and the data set was used by Lillis et al. (2012) to study secondary electron emission during SEP events, demonstrating the scientific usefulness of such data sets. Indeed, a series of X-class flares and CMEs in September 2017 interrupted the late declining phase of the otherwise relatively calm 24th solar cycle and the effects were detected by several spacecraft at Mars (see the overview paper by Lee et al., 2018). On 10 September, on the onset of the arrival of a fast CME (4 protons/cm^3, 710 km/s, 3×10^5 K) MAVEN/SEP registered the strongest fluxes of energetic particles at Mars since the start of the mission. As can be seen in Figure 1, the IMA background counts increased with a similar trend to the most energetic particles measured by MAVEN/SEP. The ASPERA-3/IMA background data allow us to quantify how extreme the September 2017 event was in comparison to the rest of solar cycle 24, and earlier, at Mars.

2. Method

The IMA ion optics assembly consists of an electrostatic deflection system, sweeping elevation entrance angles for a top hat ESA with an energy table covering 1 eV to 15 keV for most of the mission (since 2009). A postacceleration ion lens energizes ions exiting the ESA by a set energy, 2,433 eV for most orbits. A toroidal magnetic field subsequently separates the nearly monoenergetic ion beam by the gyroradii, i.e., mass per charge, of the constituent species, which is registered by impact location on a microchannel plate segmented in 16 azimuthal and 32 radial anodes (mass rings). The 96-step logarithmic energy table is covered every 12 s and the full energy elevation table every 192 s. At high energies, above a few keV, the outermost mass rings would correspond to ions with mass per charge below 1 amu/q. Counts registered by carefully chosen mass rings can thus be assumed to be free of the intended signal of the instrument and rather represent the background noise. The methodology for isolating the average background count level is described by Capalbo (2010).

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Table 1
List of Events and Corresponding Time Intervals Used to Compare Mars Express ASPERA-3/IMA and MAVEN/SEP Data

No.	Start time	End time
#1	2015-03-25	2015-03-27
#2	2015-05-05	2015-05-07
#3	2015-10-28	2015-11-09
#4	2016-01-06	2016-01-09
#5	2017-09-10	2017-09-23

Note. Dates are formatted as year-month-day.

The SEP investigation on MAVEN constitutes four double-ended solid state detector telescopes housed in two units (1 and 2) angled 90° relative to each other and 45° relative to the Sun in the nominal spacecraft attitude (Larson et al., 2015). Each telescope features an "open" aperture and a "foil" aperture, oriented opposite the other telescope in the same unit. A permanent magnet imposes a magnetic field over the open aperture, deflecting electrons with energies <350 keV. Conversely, a sheet of Kapton foil covers the foil aperture, blocking ions with energies <250 keV. Three doped silicon detectors (F, T, and O) in the telescope center allows determination of entrance direction and particle species by detection coincidence for electrons up to 600 keV and ions up to 11 MeV. Ions with energies $\gtrsim$11 MeV and electrons $\gtrsim$600 keV trigger all three detectors in a so-called FTO event. Thus, MAVEN/SEP FTO events provide information on fluxes of extremely high-energy SEPs, though without separation of particle species. While the native cadence of the instrument is 1 s, above 300 km the MAVEN/SEP data are accumulated on board to 2-, 4-, or 8-s cadence before transmission to Earth.

To avoid SEP shadowing by the planet, we only use MAVEN and MEX data taken over 0.5 Martian radii in altitude (Lillis et al., 2016) and only include MAVEN/SEP data recorded with the attenuator in the open state. The MAVEN/SEP data used here are exclusively from the SEP1B telescope since SEP1B has the open side nominally facing sunward roughly in the direction of the Parker spiral. Background IMA counts can be created by sources other than penetrating energetic particles. In certain narrow attitude ranges dense ionospheric plasma and solar ultraviolet can leak into the instrument and elevate the background level. To isolate the effects of energetic particles, we only compare IMA and MAVEN/SEP measurements taken during SEP events. Five significant events, including the September 2017 event, were identified that are covered by both IMA and MAVEN/SEP, shown in Table 1.

A set of energy-dependent response values, R_i, corresponding to the MAVEN/SEP FTO energy bins, E_i, are optimized to find the energy response of IMA background. To find representative values for R_i, we employ a genetic optimization algorithm designed to minimize the root of the sum of the squared residuals in log space, i.e.,

$$r = \sqrt{\sum \left(\log(C_{\mathrm{IMAbg}}) - \log\left(\sum_i R_i \times C_{\mathrm{SEP}}(E_i) \right) \right)^2}, \quad (1)$$

where the starting guess is 10^{-4} for all R_i. Each generation runs 1,000 mutations randomly varying by up to 10% relative to the best guess of the previous generation. The first generation with an absolute relative change smaller than 10^{-6} is taken as the final estimate. In principle, with well-determined values for R_i, the average IMA background counts should be predictable from a given MAVEN/SEP FTO spectrum.

3. Results

A comparison of raw MAVEN/SEP FTO event counts and average IMA background counts is shown in Figure 2. Each FTO spectrum is compared to the respective average IMA background count using the genetic optimization algorithm to deduce the response values, R_i, shown in Figure 3.

From the shape of the response values it would appear that IMA is most sensitive to FTO bins 10–12. FTO events in these bins are caused by $\gtrsim$1 MeV electrons and have full width at half maximum responses to protons in the following energy bands 10: 150–400 MeV, 11: 80–220 MeV, and 12: 50–150 MeV. However,

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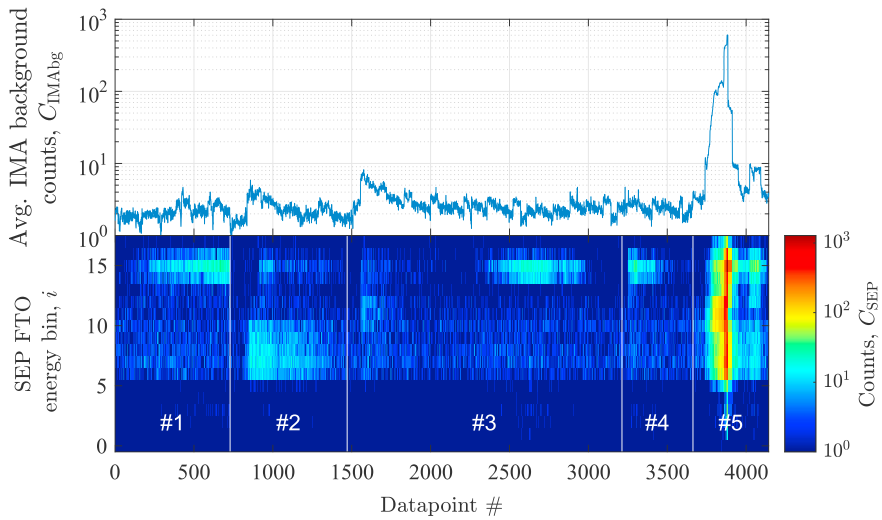

Figure 2. Average IMA background counts and raw MAVEN/SEP spectra for the five SEP events identified and utilized in this study; see Table 1. MAVEN/SEP = Mars Atmosphere and Volatile Evolution Solar Energetic Particle; IMA = Ion Mass Analyzer.

the typical energy distribution during SEP events implies that a disproportional amount of the counts is produced by protons with lower energies, such that FTO bin 12 represents protons down to 20 MeV. Conversely, IMA appears only weakly sensitive to particles generating FTO events in bins 13–14, which are insensitive to electrons and are largely responding to protons ≲20 MeV. IMA is not sensitive at all to the ∼10–20 MeV protons registering as FTO events in bins 15–17. However, IMA is clearly sensitive to particles generating FTO events in bins 6–9, which are strongly dominated by >1 MeV electrons, though protons with energies from several 100 MeV up to 1 GeV would be sorted to these bins. Protons with energies >1 GeV would be sorted exclusively to bin 6. Bins 0–5 only register noise. It should be noted that these energy ranges are preliminary estimates and part of ongoing work.

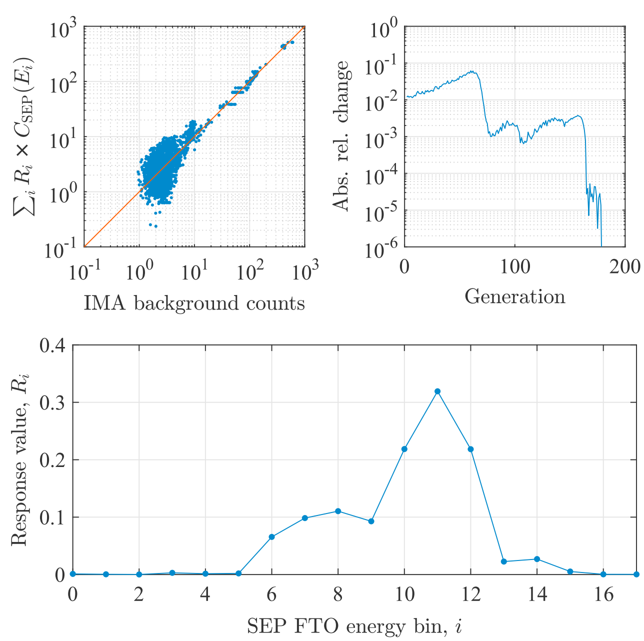

Figure 3. Result of the genetic optimization algorithm for obtaining the most representative energy response of the IMA background. (top left) IMA background counts and reconstructed IMA background counts based on the final estimated response values. (top right) Absolute relative change in the residual parameter, r, for each generation. (bottom) Final estimation for the response values, R_i. IMA = Ion Mass Analyzer.

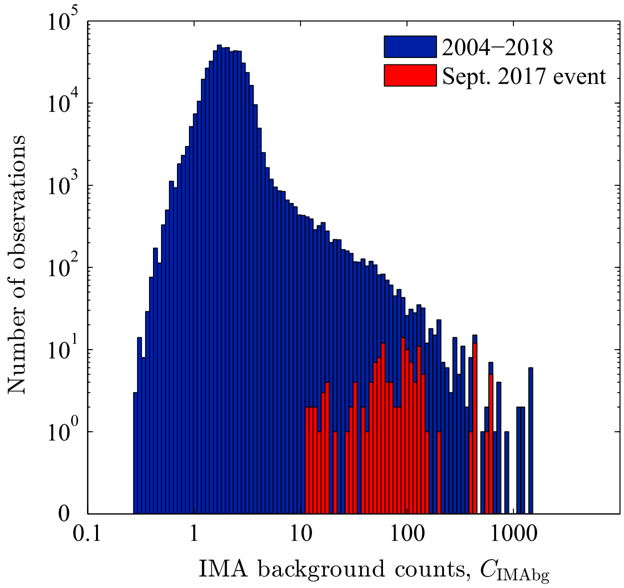

Figure 4. Distribution of average IMA background counts, each observed over the 12 s IMA energy sweeps, for the duration of the Mars Express mission (blue) and for the September 2017 event (red). The background counts higher than the peak counts from September 2017 were measured during three separate previous events in 2005, 2011, and 2012. IMA = Ion Mass Analyzer.

The distribution of IMA background counts over the last 14 years and the September 2017 event are displayed in Figure 4, clearly showing that the peak energetic particle flux during the September 2017 event was extreme in the $\gtrsim$1 MeV electron/>20 MeV proton energy ranges IMA appears most sensitive to. Only a handful of SEP events observed by MEX over the last solar cycle reached intensities higher than the September 2017 event, which peaked at 606 background counts. The highest average background count recorded by IMA in the selected data was 1,471 counts on 27 January 2012 at 23:52:00, followed by 1,056 counts on 6 June 2011 at 13:55:21, and 700 counts on 28 April 2005 at 02:37:48. All counts are collected over a 12 s full energy sweep of the ESA.

4. Discussion and Conclusions

The lack of systematic separation of protons and electrons in the MAVEN/SEP FTO data precludes determining to which type of particle IMA is most sensitive. Nevertheless, IMA appears sensitive to energetic >20 MeV protons and $\gtrsim$1 MeV electrons as both are expected to generate the counts measured in FTO bins 10–12, electrons dominating in bins 6–9, and only protons registering in bins 13–14. A lower limit ~20 MeV for penetrating protons is consistent with the ~30 MeV lower energy limit for energetic particles triggering background counts in the MGS/ER instrument found by Delory et al. (2012). Limits near these values are expected as required to penetrate the typical aluminum housings of electrostatic plasma analyzers.

The varying attitude of MEX is not taken into account in this study and may introduce some bias in the background data due to SEP shadowing by the spacecraft. However, the wide angular spread of SEP distributions (Lillis et al., 2016) implies that this effect is likely small. Indeed, the strong correlation between IMA background counts and expected IMA background counts from MAVEN/SEP FTO data ($\rho = 0.85$ in log/log space, Figure 3) demonstrates that the IMA data can be reliably used to estimate fluxes of energetic particles. In future studies we intend to calibrate the IMA background to physical fluxes as measured by MAVEN/SEP and properly account for the varying attitude of MEX.

The distribution of IMA background counts since 2004 shows that the SEP flux during the September 2017 event was extreme in the energy range for which IMA is sensitive to penetrating particles. Note that IMA has not operated continuously for the duration of the mission and some gaps exist in the coverage over time; thus, this distribution technically only represents the periods observed by IMA. As such, the peak flux during the September 2017 event was the fourth strongest observed by MEX since the beginning of the mission in 2004.

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