Solar energetic particle events detected in the housekeeping data of the European Space Agency's spacecraft flotilla in the Solar System

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Key Points:

- Space weather detections using housekeeping datasets on ESA spacecraft
- Some engineering datasets on spacecraft have the potential to be used for science
- Same Space Weather events detected with housekeeping data at widely-spaced locations in the Solar System

Key Words:

Space Weather, housekeeping, solar energetic particles, SEP events

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Abstract

Despite the growing importance of planetary Space Weather forecasting and radiation protection for science and robotic exploration and the need for accurate Space Weather monitoring and predictions, only a limited number of spacecraft have dedicated instrumentation for this purpose. However, every spacecraft (planetary or astronomical) has hundreds of housekeeping sensors distributed across the spacecraft, some of which can be useful to detect radiation hazards produced by solar particle events. In particular, energetic particles that impact detectors and subsystems on a spacecraft can be identified by certain housekeeping sensors, such as the Error Detection and Correction (EDAC) memory counters, and their effects can be assessed. These counters typically have a sudden large increase in a short time in their error counts that generally match the arrival of energetic particles to the spacecraft. We investigate these engineering datasets for scientific purposes and perform a feasibility study of solar energetic particle event detections using EDAC counters from seven ESA Solar System missions: Venus Express, Mars Express, ExoMars-Trace Gas Orbiter, Rosetta, BepiColombo, Solar Orbiter and Gaia. Six cases studies, in which the same event was observed by different missions at different locations in the inner Solar System are analysed. The results of this study show how engineering sensors, e.g., EDAC counters, can be used to infer information about the solar particle environment at each spacecraft location. Therefore, we demonstrate the potential of the various EDAC to provide a network of solar particle detections at locations where no scientific observations of this kind are available.

Plain Language Summary

Space Weather is the discipline that aims at understanding and predicting the state of the Sun, interplanetary medium and its impact on planetary environments. One source of Space Weather is Solar Energetic Particles (SEPs), which are emitted by the Sun and enhance the radiation and particles that flow in space. Predicting the motion of these particles is important but difficult as we need good satellite coverage of the entire inner Solar System, and only a limited number of spacecraft have the necessary instrumentation. Thanks to the European Space Agency (ESA) flotilla, i.e., Venus Express, Mars Express, ExoMars-Trace Gas Orbiter, Rosetta, BepiColombo, Solar Orbiter and Gaia, we performed a feasibility study of the detection of SEP events using engineering sensors in the main body of the spacecraft that were originally placed there to monitor its health during the mission. We explored how much scientific information we can get from these engineering sensors, such as the timing and duration of an SEP impacting the spacecraft, or the minimum energy of those particles to trigger a detection. The results of this study have the potential of providing a good network of solar particle detections at locations where no scientific observations are available.

1. Introduction

Monitoring planetary Space Weather in the Solar System is currently a challenging but essential activity that requires a good knowledge of the Sun and solar wind conditions, the local space environments (including solar wind-magnetosphere-ionosphere coupling), and the interaction of each spacecraft with its local environment. Consequently, understanding the chain of processes that control Space Weather at any planet or spacecraft on various time scales is important to accurately forecast and prevent hazardous conditions for a mission, and ultimately humans, throughout the Solar System (e.g., Plainaki et al., 2016; Sanchez-Cano et al., 2021; 2023a). At the moment, there are several national monitoring programs in place for terrestrial Space Weather forecasting, for which, most of the information about radiation hazards comes from near-Earth satellites, with a few exceptions such as the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) (Spence et al., 2010) and Lunar Lander Neutron and Dosimetry (LND) (Wimmer-Schweingruber et al., 2020) instruments on the surface of the Moon. However, as we expand our robotic exploration within the Solar System, monitoring planetary Space Weather is becoming more important than ever. This is particularly important for Mars, which is currently a major target of planetary exploration and possibly soon for human exploration.

Despite this, not every spacecraft is designed to detect radiation and only a few of them come with the necessary instrumentation for radiation measurement and Space Weather purposes. However, all of them have a large number of housekeeping detectors distributed across the spacecraft to monitor its health and that of the payload during the lifetime of the mission. The Error Detection and Correction (EDAC) memory counters are among these housekeeping detectors (Shirvani et al., 2000). EDACs are pieces of code that protect memories in a spacecraft computer from bit-flips caused by single event upsets (SEU). In other words, when an energetic particle hits a physical memory cell and deposits charge in it, a memory error may occur corrupting the data stored on the chips if not corrected (Shirvani et al., 2000; D'Alessio et al., 2013; Knutsen et al., 2021). This effect is non-destructive and reversible by resetting or rewriting the device. SEUs corrected by EDACs are normally registered in a relevant counter by increasing it by 1. There are also other types of errors, such as the Single-Event Functional Interrupt (SEFI), which refer to addressing errors in memories. In this case, the control circuitry of the memories, that controls the access to the stored data, is affected. The outcome of a SEFI depends on which part of the logic circuitry is hit. They can be caused by different mechanisms which are sensitive to SEUs like any memory cell. As a result, a burst of errors can occur. Figure 1 displays a diagram of how the memories read and catalogue the events, which helps distinguish between nominal operations, SEUs and SEFIs. Specifically, EDACs are implemented in memories by using additional memory bits/cells that can be compared to the original stored information and detect errors in its content. The simplest EDAC uses a parity bit. Assuming that 7 bits of information are stored in a word, an additional parity bit is written as a 1 if the number of 1s in the word is odd, or as a 0 if the number of 1s in the word is even. If the number of 1s in the 7-bit word is odd but the parity bit is 0, an upset must have occurred. This algorithm is very limited. As it does not provide information about which bit is erroneous, it cannot be corrected and, therefore, the data are lost. It also does not allow detection of an even number of errors. For space applications, more powerful algorithms that allow detection and correction of single errors and detection of multiple errors are used. In this case, if a SEU occurs, EDACs are able to identify the bit where the error occurred and correct it. When Multiple Bit Upsets (MBUs) occur, EDACs cannot correct the errors but may still flag them. Multiple Cell Upsets (MCUs) and SEFIs will cause the EDAC to detect errors up to thousands of words (depending on memory technology and implementation). While MCUs can be corrected by EDACs, in SEFIs this is not always the case. This is because SEFIs occur in the control part of the memories and not on the memory cells themselves (see Figure 1). It is not straightforward to distinguish between events such as SEUs/MCUs/MBUs from SEFIs without operational knowledge. This is the main reason why in this study we only focus on SEUs and on those distinct SEFIs caused by solar particle events.

In a previous study, Knutsen et al. (2021) demonstrated that several EDAC counters of the Mars Express and Rosetta missions were sensitive to galactic cosmic rays, based on analyses of long-term series of SEUs from EDAC counters. In particular, Knutsen et al. (2021) revealed a time lag of 5.5 months in the solar cycle modulation of galactic cosmic rays at both spacecraft, as well as a 4.7±0.8% increase in the galactic cosmic ray flux per astronomical unit, which matched very well with previously published literature (e.g., Honig et al. 2019). Most importantly, Knutsen et al. (2021) demonstrated the scientific potential of these engineering datasets. Nevertheless, despite several of them being publicly available at the European Space Agency (ESA) Planetary Science Archive (PSA), EDACs remain mostly unexplored. In addition, EDAC datasets have shown some promising signs of also being sensitive to short-term radiation activity, such as Solar Energetic Particles (SEPs) and Interplanetary Coronal Mass Ejections (ICMEs) (e.g., Jiggens et al. 2019, Figure 21). However, no systematic study has been performed so far, and only a small step has been taken towards developing the scientific potential of this dataset.

The goal of this study is to investigate and exploit this dataset for scientific purposes by performing the first comprehensive feasibility study with simultaneous detections of SEP events at different locations in the Solar System using EDAC counters from the following 7 ESA Solar System missions: Gaia close to Earth (at Earth Lagrange point 2, L2, Prusti et al., 2016), Venus Express at Venus (Svedhem et al., 2009), Mars Express (Chicarro et al., 2004) and ExoMars Trace Gas Orbiter (here after ExoMars-

TGO, Vago et al., 2015) at Mars, Rosetta at comet 67P/Churyumov-Gerasimenko (here after comet 67P, Taylor et al., 2017), and BepiColombo (Benkhoff et al., 2010) and Solar Orbiter in the interplanetary medium (Müller et al., 2020; García-Marirrodriga et al., 2021). Unfortunately, no EDAC data from the Huygens probe (Lebreton and Matson, 2002) are available as it was only connected twice per year during the cruise to Titan to check the health of the spacecraft. We do not consider Cluster-II (Escoubet et al., 2001) or any other mission crossing the radiation belts at Earth as the data analysis in these cases is more complex due to combined radiation effects from the Van Allen belts, Earth's magnetosphere and SEP events. Although not all of the missions in this study were active at the same time, they provide a good network of solar particle observations at locations where such observations are not necessarily available (e.g., when scientific instruments are off or when the payload did not include an energetic particle instrument). Solar Orbiter and BepiColombo include such instruments and are used for direct comparison in this paper. The seven missions of this study cover heliocentric distances of ~0.3-5 au and the time period from 2003 to the present.

2. Datasets

Several housekeeping datasets, mainly EDAC counters from the aforementioned ESA missions have been used in this feasibility study. Moreover, in order to corroborate the existence of a simultaneous Space Weather event and give context to the housekeeping observations, several scientific datasets from the same ESA missions (when available) and other missions have been included, as described in the following.

2.1. EDAC (housekeeping)

All spacecraft have several EDAC counters distributed across the spacecraft. In particular, we use the EDAC variables listed below which are sensitive to energetic particles. They have been chosen because they report increments multiple times per day, i.e., have sufficient time resolution to provide information about solar particle events. The average counts per day before and after the events of this study are indicated below. The following numbers are the identifiers (ID) at the ESA housekeeping archives:

- Gaia: IDs 0.NDW62014, 0.NST82031, 0.NST82031, 0.NV102604, 0.NV302604. Average 0.2 counts/day.
- Mars Express: ID NDMW0D0G, same as the counter used by Knutsen et al. (2021) for galactic cosmic rays. Average 0.7 counts/day.

- ExoMars-TGO: ID ASA11F0L. Average 0.07 counts/day.
- Venus Express: ID NDMW0D0A. Average 0.5 counts/day.
- Rosetta: ID NACW0D0A, same as the counter used by Knutsen et al. (2021) for galactic cosmic rays. Average 0.7 counts/day.
- BepiColombo: IDs NCDT2490, NCDT24A0 and NSM00798. Average 0 counts/day.
- Solar Orbiter: IDs NSM00798, NSM00799, NSM00800, and NCDT07B0. Average 1.83 counts/day. In addition, we use the total count of SRAM EDAC, and the total single bit correctable EDAC errors from the Solar Orbiter Heavy Ion Sensor (HIS) part of the Solar Wind Analyser (SWA) suite of instruments (Owen et al., 2020). Average 3.08 counts/day.

All these EDAC parameters are archived by the European Space Operations Centre (ESOC). Several of them are publicly available at the European Space Agency Planetary Science Archive (e.g. Rosetta, Cluster-II); some others were not systematically archived in the past because they were originally not considered to be scientific data. The EDAC datasets used in this work have been gathered into a publicly accessible archive at Sanchez-Cano et al. (2023b).

2.2. Other scientific datasets

- Earth: We use OMNI 2 data (King and Papitashvili, 2005), where energetic particles and other plasma parameters are available from a compilation of observations from 20 spacecraft near Earth at a time resolution of one hour. In particular, the SEP data come from the GOES satellites.
- Mars: We use the background particle detections from the Mars Express Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) instrument (Barabash et al., 2006). The background detections are caused by electrons with energies >1 MeV and protons >20 MeV that penetrate the walls and internal structure of the instrument and register as background counts on the microchannel plates (Futaana et al., 2008; 2022; Ramstad et al., 2018). In addition, we use the scintillator block of the Mars Odyssey-High Energy Neutron Detector (HEND), which is used to remove background noise, such as galactic cosmic rays (GCRs), energetic photons or SEP events (Zeitlin et al., 2010, Livshits et al., 2017; Sanchez-Cano et al., 2018) and have a sensitivity limit of ~2.5 MeV for high radiation fluxes. We also use the Radiation Assessment Detector (RAD) on board the Mars Science Laboratory (MSL) (Hassler et al., 2012) at the surface of Mars. In particular, we use the L2match-5 count rate. Because the Martian atmosphere provides approximately 21 g/cm^2 of shielding at the location of MSL, RAD is only sensitive to particles with energies above ~160 MeV/nuc. We note that data from the Liulin-MO dosimeter, which forms

part of the FREND instrument on the ExoMars Trace Gas Orbiter, were not available at the time that the present study began, but are now available at the ESA PSA.

- Venus: We use the background particle detections from the Venus Express Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4) instrument (Barabash et al., 2007), similar to ASPERA-3 in Mars Express (Futaana et al., 2022).
- Comet 67P: We use the Standard Radiation Environment Monitor (SREM) (Evans et al., 2008; Honig et al., 2019), which provides intensity of detections in counts for protons and electrons in 15 different channels starting at ~0.8 MeV for electrons and ~2MeV for protons.
- BepiColombo: We use the BepiColombo Radiation Monitor (BERM), which measures electrons with energies from ~100 keV to ~10 MeV and protons with energies from 1.35 MeV to ~100 MeV (Pinto et al., 2022). We also use the BepiColombo Planetary Magnetometer (MPO-MAG) for the interplanetary magnetic field (IMF) context (Heyner et al., 2021) in ecliptic J2000 coordinates.
- Solar Orbiter: We use penetrating particle observations from the Energetic Particle Detector (EPD) (Rodríguez-Pacheco et al., 2020, Wimmer-Schweingruber et al., 2021). In particular, we use the High-Energy Telescope (HET) single counter in four different channels: HETG_0, which is a counter for BCB coincidence (B and C are detectors) with energy depositions in the C detector of 15-30 MeV and primary energy above 370 MeV; HETG_1, which is a counter for BCB coincidence with energy depositions of 30-56 MeV in the C detector and corresponds to protons with a primary energy 150-370 MeV; C_L, which is a single counter detector C with more than 10 MeV deposited in it, and the C_H, which is a single counter detector C with more than 4 MeV deposited in it.

3. Solar Energetic Particle event detection with EDAC counters

EDAC data are stored in the form of cumulative counters. There are occasional cases in which a counter is reinitialized due to technical issues by ESOC command. Those cases are not considered in this study. It is important to note that the frequency of EDAC observations is irregular, it can vary from single observations taken every 30 s to one measurement per day (see Section 2.1). Moreover, as described by Knutsen et al. (2021), long time series are affected by the modulation of the GCR flux with the solar cycle. However, in this study, we consider this long-term modulation as negligible because solar particle events typically only last a few days. Moreover, the count rate increase due to GCR flux in the EDAC counts is on average 0.1-3 counts per day (see Section 2.1), while a SEP event typically creates a sudden increase of tens counts per day.

A solar particle event (or Space Weather detection) is seen as a statistically significant rapid enhancement (on the order of several hours) in the EDAC counters, coincident with a simultaneous arrival of solar energetic particles. A rapid increase can be caused by random fluctuations in the GCR background (considered negligible in this study), but also by SEPs. Figure 2 shows two examples of EDAC detections of SEP events at two different locations, i.e., at comet 67P by Rosetta and at Earth's Lagrange point 2 (L2) by Gaia. These missions were designed for different scientific purposes, Rosetta was a cometary mission travelling within a large part of the inner Solar System, and Gaia is an astronomical observatory placed at the Earth's L2 point. Despite this, these spacecraft have EDAC counters that make the potential detections of solar particle events plausible. The EDAC counters, without any correction, are shown as black time series (profiles) in Figure 2 and the SEP event that hit each of the spacecraft is shown as colored time series as indicated in each panel.

Figure 2a shows a case detected by Rosetta when it was at 1.07 au, where SEP observations come from the SREM monitor. As can be seen, there are two significant jumps in the EDAC profile on the 17th and 20th of January 2005 at the same time that two SEP events hit the spacecraft. The second of these events corresponds to a ground-level enhancement (GLE) event observed at Earth. The number of high energy particles is lower on the first event, and as a consequence, the rise in EDACs is moderate, while the second event has a prompt and large increase in the most energetic channel of SREM (about an order of magnitude larger than the previous case) that coincides with a very large and sudden rise in the EDAC profile. In particular, there is an increase of 50 counts in less than a day, while on average the increase is of 0.7 counts/day during no SEP events (which could be considered, to a first order, as the GCR background). The difference in the increase of these two events and the change in the order of magnitude in the pink profile for both events indicate that protons of >49 MeV energies are likely to trigger these EDAC increases at Rosetta.

Figure 2b shows an event measured by Gaia, in which case the SEP observations come from the OMNI database at 1 au. This SEP event is most probably the combination of two events starting on the 18th and late 21st of June 2015. Despite the difficulty and limitations of comparing counts and flux units in these two events, the presence of high energetic particles >30 MeV in the OMNI data seems lower than in Rosetta with also a less sharp onset, but still it was able to produce a rise in the Gaia EDAC counter, particularly the second SEP event peak where fluxes are the largest. However, since the change in the flux magnitude for the second event is not as dramatic as for the Rosetta case, it is difficult to conclude which energies are more likely to trigger an event in this EDAC counter when considering only this case (a second Gaia event is discussed in Section 3.3). We note that we have used three representative energy channels from OMNI but particles with energies between the last two channels could trigger the event as in the case of Rosetta. This will be better characterised with a larger event in Section 3.3. It is interesting to note that the event starts several minutes after it is seen in OMNI. As will be discussed later, this could be the consequence of several factors, such as the data sampling. We note that although there is a single error caused probably by the first SEP event arrival on the 19th of June, we cannot conclude that this is a real effect of the SEP event as there is a similar error occurring on the 5th of July where we do not have a significant rise in the particle flux.

To better understand the origin of these sudden increases in EDAC counters, as well as to potentially determine whether they can be used to detect SEP events, we have selected six well-known SEP events that were widely spread in the inner Solar System and hit several spacecraft. Figure 3 shows the locations of several ESA spacecraft at the time of the events and the arrow at the Sun shows the direction of the solar flare/coronal mass ejection (CME) that produced the SEP event. The following subsections describe the observations for each of the events.

3.1. Solar particle event on 5 December 2006

On 5 December 2006 at 10:35UT, an X9.0 solar flare and a large SEP event were reported headed in the direction of Mars and Venus (Futaana et al., 2008). In addition, the spacecraft Rosetta was relatively close to Venus and Mars and also saw this event. Figure 4 shows the EDAC observations from Mars Express (panels a-b), Rosetta (panels c-d) and Venus Express (panels e-f) as black profiles as well as the SEP event observed by other scientific instruments in colors as indicated in the figure. The bottom panels of each subset (b, d and f) have the actual SEP event profiles measured by ASPERA-3 (light blue) in panel b, SREM (pink and green) in panel d and ASPERA-4 (purple) in panel f. The upper panels (a, c and e) show the cumulative version of the profiles in the bottom panels, with the exception of the green profile in the Rosetta plot as it does not have enough statistics. As can be seen, both Mars Express and Rosetta have a gradual increase in the EDAC counter during this event that coincides with the starting time of the event, as well as with the cumulative sum profiles in both cases. There was a second increase on 7 December, probably related to the X6 solar flare that produced a large solar corona shock wave, typically referred as “solar tsunami”, which is sharper at Venus as it was better located with respect to the source at the Sun. Despite the data gaps in ASPERA-4, the matching of the onset time and slope of the increase is consistent with this second event. We note that for Rosetta, most of the SREM counters did not have enough statistics (enough datapoints) to perform the cumulative sum per channel, and instead we have done the cumulative sum of all the channels together. This is the main reason for the sharp increase in the pink profile.

3.2. Solar particle event on 7 March 2012

Figure 5 shows observations of one of the largest solar particle events that we have witnessed at Mars and Venus. It occurred in 2012, and it was observed by Mars Express ASPERA-3 background counts, HEND and MSL-RAD during the MSL cruise phase from Earth to Mars. In the particular case of Venus, the event is the largest one observed by Venus Express, where the star trackers were blind for 5 days. This is the main reason why there is a data gap in the ASPERA-4 background observations (in purple). At Mars, the EDAC profile shows an increase in error detections coincident with the onset of the SEP event in the flux measurements starting on the 7th which is followed by a largest rise on the 9th that corresponds to the largest observed fluxes. We note that both HEND and ASPERA-3 show similar profiles while RAD detected a shorter increase. The main reason for the RAD detection is that MSL was still in its cruise phase at 1.25 au but due to the Hohman-Parker effect saw the same event as it was well-connected magnetically to Mars (Posner et al., 2013).

3.3. Solar particle event on 10 September 2017

This is one of the biggest events with the largest fluence of solar energetic particles that occurred during solar cycle 24. The sunspot Active Region (AR) 12674 produced several consecutive solar flares, including an X9.3 flare with a peak X-ray flux at approximately 12:02 UTC on 6 September 2017 (the largest X-ray flare of that solar cycle). This flare was approximately directed towards Earth (not shown in Figure 3), but the associated flux of particles at higher energies (>100 MeV) was moderate. Instead, another X8.2 solar flare (shown in Figure 3) that peaked at 16:06 UTC on Sunday 10 September 2017 was associated with a very wide spread SEP event that hit both Earth and Mars (e.g. Jiggens et al., 2019). Both of these events were accompanied by fast CMEs and interplanetary shocks that hit Earth and Mars, respectively, where the second was the largest ICME encountered by Mars Express at Mars (e.g., Lee et al., 2018; Sanchez-Cano et al., 2019; Lester et al., 2022).

Despite the large angular distance between Earth and Mars (~155°, see Figure 3), the SEP event was clearly seen at both planets. Figure 6 shows the EDAC observations from Mars Express and ExoMars-TGO at Mars (panels a-b) and Gaia at Earth (panels c-d) as black/grey profiles as well as the SEP event observed by other scientific instruments in colors as indicated in the figure. The bottom panels (b and d) have the actual profiles measured by HEND (dark blue), MSL-RAD (green), ASPERA-3 (light blue), and OMNI (light green, cyan and pink). The upper panels (a and c) show the cumulative versions of the profiles in the bottom panels. As can be seen, the SEP event starting on the 10th at Earth had a clear effect on the EDAC profile with a large increase when more energetic protons (>60 MeV) arrived with fluxes an order of magnitude larger with respect to the previous SEP event on the 4th. Moreover, the slopes of both the EDAC and the cumulative SEP observations are similar, confirming the origin of this detection. Regarding the first SEP event, after considering Gaia observations in Figures 2 and 4, the small increase on the 4th in Figure 4 indicates that a flux of particles >10^2 ($cm^{-2}s^{-1}sr^{-1}MeV^{-1}$) with energy of >10 MeV can start triggering an event in the Gaia EDAC memory counter. In this Figure, there are also a couple of potential extra events on the Gaia EDAC on 3 and 23 September, respectively. They are not associated with a corresponding SEP event, and a good way to discard them is because their increase rates are of the same order of the average rate (see Section 2.1), much slower and rise less drastic than the actual increases caused by SEP event.

For the case at Mars, only the second SEP event on the 10th hit the red planet and the EDAC counters of both Mars Express and ExoMars-TGO clearly registered the event. We find a similar slope between the EDAC and the SEP cumulative summed profiles although with a small delay of several minutes in the onset of ExoMars-TGO and HEND, which we attribute to differences in their orbits. Mars Express is on a more elliptical orbit than Mars Odyssey and ExoMars-TGO, which are in a circular orbit closer to the planet. This effect can also be responsible for the varying EDAC rate, as well as because HEND was saturated during this event as can be seen on the flat top of the profile between days 11 and 13. This saturation may be contributing to some differences in the slop of its cumulative sum. Finally, the MSL-RAD cumulative sum has not been calculated for this case as the SEP event is much shorter than for HEND and ASPERA-3. The main reason may be because MSL is an observatory on the Martian surface and therefore, the incoming particles are attenuated by the atmosphere, e.g., protons need at least ~160 MeV to penetrate the 21 g/cm² of Mars's atmosphere. Thus MSL-RAD measures particles at much higher energies than the energy range of the other two instruments, HEND and ASPERA-3, which are in orbit and can see lower-energy particles. Nevertheless, we note that the SEP event onset starts at the same time as for the other two instruments, as well as the maximum of the event. To conclude the discussion of this event at Mars, the reason for the drop on the 13th (matching also a rapid decrease in HEND data at the same time) is the arrival of the ICME and the associated Forbush decrease (Guo et al., 2018; Ehresmann et al., 2018).

3.4. Non-detection of Solar particle event on 28 October 2021

Figure 7 shows the SEP event of 28 October 2021, which is a non-detection event on EDAC counters. The structure of the figure and color code is the same as the previous figures, with the EDAC profiles in black and the SEP detections in colors as indicated. This event was an impulsive X1 solar flare that started at 15:35 UTC on 28 October from the Active Region 2887 and it was followed by a CME. It even created GLE event at Earth. It was a very widely spread SEP event that was seen at least by Mars' missions and Solar Orbiter, which were separated by nearly 180° in longitude. The event was directed toward Earth and Solar Orbiter, and therefore, Mars was only impacted by a very moderate SEP event which was four orders of magnitude smaller than the previous events shown in this work as seen by ASPERA-3. This may be the reason why there was no increase in the Mars Express' EDAC counters. The EDAC profile shows several increases, but none of them are significant enough to be considered an event and none of them match the arrival time of the SEP event. We note that ExoMars-TGO EDAC counters do not have any clear detection either and the data are not shown because there is a reboot of the memory at the end of the period of the event.

Solar Orbiter was directly impacted by the SEP event as demonstrated by EPD data (Figure 7c-d). However, the EDAC profiles do not show any significant increase. There is a single error at the time of the event onset but we note that it is not statistically significant to be considered a detection. Moreover, there is another one day and a half after which there is no corresponding large increase in the SEP flux, which is expected since the average daily EDAC rate is ~1.3. Therefore, we can only conclude that Solar Orbiter EDAC counters did not detect this SEP event. Although the spacecraft may be more protected by a heat shield, the instruments are placed externally to the spacecraft and also have EDAC counters. For this reason, we have selected EDAC counters on one instrument of Solar Orbiter, the Heavy Ion Sensor (HIS) sensor of the Solar Wind Analyser (SWA) suite of instruments, which is mounted within a cut-out in the corner of the spacecraft heat shield (Owen et al., 2020). The main reason for this is to understand if the non-detection by the spacecraft EDAC is due to the shield or something else. Unfortunately, SWA-HIS was disconnected during this event (for other observations, see Section 3.6).

3.5. Solar particle event on 15 February 2022

Another interesting SEP event occurred on 15 February 2022, which was widely spread in the inner Solar System, and was followed by a CME. The solar eruption started at ~21:50 UT on 15 February from the sunspot group complex NOAA AR 2936–2938 (these active region numbers are referred to those during the previous disk passage as this flare occurred on the far side), and its intensity is unknown as the flare emission occurred in the occulted Sun's surface with respect to Earth and other solar observatories (e.g., Mierla et al., 2022). However, we know it was directed towards BepiColombo at ~170° from Earth's direction and about 90° with respect to Mars. The associated SEP event was weak at Earth and not observed at Solar Orbiter, while BepiColombo and Mars had the best observations.

Figure 8 shows the EDAC observations for both Mars Express at Mars (panels a-b) and BepiColombo (panels c-e) as black profiles as well as the SEP event observed by other scientific instruments in colors as indicated in the figure. As in the previous figures, the bottom panels (b and d) have the actual SEP profiles measured in this case by MSL-RAD (green) and ASPERA-3 (light blue), and BERM (shades of red), and the upper panels (a and c) show the cumulative version of the profiles in the bottom panels. We do not show HEND data for this event as they are not publicly available at the time of writing. Also, we do not show ExoMars-TGO EDAC observations as the memory had an automatic restart during the event. In addition, for interplanetary context, the IMF observed by MPO-MAG has been added in panel e.

Starting with the Martian case, the EDAC increase is less abrupt than in previous figures, but still significant and has the same slope as the other SEP profiles. Regarding BepiColombo, despite having the “best-front-view” of the SEP event, the observations are less clear. The increase is seen as three bursts resembling a SEFI but more details about the counters and their operations are required to catalogue these errors as SEFIs. We also would like to remark that so far in the cruise phase of the BepiColombo mission, this is the first clear detection of a SEFI/SEU on the BepiColombo EDAC counters after a SEP event, coinciding with the first time that BERM detected protons of >60 MeV. Since the delay time between the onset of the SEP and EDAC event (which depends on scrubbing/access time) is larger than in the previous cases, we have also plotted the IMF components to show that the ICME arrived at BepiColombo a few hours later during the maximum of the SEP event (IMF>50 nT on 16 February 2022), which may have contributed to trigger the onset in the EDAC counters of BepiColombo.

3.6. Solar particle event on 5 September 2022

The last event we discuss is the SEP event and very large halo CME event that was ejected from the Active Region AR 3088 on 5 September 2022. It was directed toward Venus and Solar Orbiter was very close. This is the perfect candidate to understand whether the EDAC counters on Solar Orbiter can be actually used as SEP monitors. Figure 9 shows the EDAC counter of the spacecraft in black in panel a, while EPD observations of ions and electron spectra are shown in panels b and c, respectively. We do not show in this case HET penetrating data as in Figure 7 because this event had extremely high-count rate and some internal work is being done within the team to solve the issue. For that reason, we show the quick-look plots provided by the team. As can be seen, despite being one the most energetic events that have hit Solar Orbiter, the EDAC memory on the spacecraft do not show any rise during the event, a rise is only observed after the event has passed, which is not related to the SEP event.

As in Section 3.4, in order to understand if the non-detection by the spacecraft EDAC is due to the heat shield or to something else, we use the EDAC memory of the SWA-HIS sensor (in orange in panel a). For this event the instrument was in operation and registered the largest increase in EDAC of the mission so far. As can be seen, an increase of about 200 errors in less than half a day was detected on the memory starting on the 5th of September, and having the maximum on the 6th, corresponding very well with the arrival and peak intensity of the highest energy part of the SEP event recorded by EPD. The clear detection by SWA-HIS EDAC and the non-detection by the spacecraft EDACs confirm that either those memories on the spacecraft are most probably well protected from the upcoming radiation, or that the spacecraft memory is not sensitive to these events.

Finally, we note that a SEP event arrived at BepiColombo on 7 September 2022, which most probably is associated with a different flare. Although not shown here, we note that BepiColombo EDACs do not show any significant increase.

4. Discussion

Engineering data-sets, though not designed for science purposes, could be a very useful scientific resource. This is especially important when investigating solar energetic particle propagation in the Solar System as our current observations come from a very limited number of locations, and not all missions have the right instrumentation to detect them. In this work, we have performed a feasibility study in order to investigate whether engineering memories/counters present in all spacecraft, such as EDACs, could be useful for these tasks. This is an important first step in order to systematically exploit the EDAC counters for scientific purposes, as well as other spacecraft/instrument memories in the future. Thanks to the spacecraft flotilla that ESA has in the Solar System from 2003 between ~0.3-5 au, we have the opportunity to perform this feasibility study with several case studies of well-spread SEP events in the inner Solar System that have allowed us to prove that some EDACs respond to solar particle events.

Although these datasets do not provide accurate observations or flux measurements of the SEP events, the indirect detection of an SEP event by an EDAC memory can be important for solar wind modellers, particle propagation studies, as well as for transient propagation studies. A clear example was shown by Witasse et al., (2017) where the propagation of a very large ICME through the entire Solar System was investigated. Although the ICME hit Venus in its journey, no observations from science instruments on Venus Express were available because Venus was in superior solar conjunction with Earth. However, thanks to EDAC counters on Venus Express, Witasse et al., (2017) were able to detect the arrival time of the event, which was extremely useful to the investigation as they had an additional data point to constrain the propagation models used in that study.

For each spacecraft, there are thousands of housekeeping parameters that may warrant further exploration, not only EDACs, which may also provide useful scientific information. However, we note that the advantage of EDAC counters is that there is a sufficient number of SEUs to provide good statistics, while although other parameters are occasionally affected by SEUs, the frequency of such events may not be high enough. A further investigation of other housekeeping parameters will be performed in the future. We also note that examination of these datasets is a particularly challenging task as the parameters are not properly described and for which dedicated help from operations and engineering staff of each mission is needed.

It is important to note that the response of EDAC counters is not the same for all spacecraft. The main reasons are that the memory models, number of memories used, and spacecraft shielding are different from each spacecraft, either by design or in combination with the structure of the spacecraft. A second-order effect may be the shielding material, but that is more important for very high energy particles, particularly GCRs. In addition, the sensitivity of the memory chips used on different spacecraft to radiation induced SEUs is also likely to be significant. Moreover, not every spacecraft has the sensors in the same place. To make a proper characterization of the shielding, original CAD models of the spacecraft are needed. However, although we have tried to obtain them for Mars Express and Rosetta, these missions are now very old and this information, which belongs to industry, is not available anymore. This is a learning point derived from this investigation as for new and upcoming missions, we recommend that all relevant sensors, shielding and spacecraft models should be made available for the scientific community as well.

Other SEFIs or SEU rises may occur at any time on EDAC counters, which are typically used by ESOC to monitor the safety of the spacecraft. These rises could be due to many different factors, such as changes in attitude, problems with instruments, high voltages, etc. In all cases in this study, we verified that nothing else was occurring on the spacecraft which is what leads to the assertion that these detections are genuinely produced by solar particle events. For future studies that need EDAC detections, we recommend cross-checks between multiple data sources and with operations schedules to reduce false positives.

Finally, from all missions considered in this study, Mars Express is the spacecraft that has proven to be the most sensitive for EDAC SEP detections. Thanks also to its long life at Mars, we have plenty of observations that we can use to better characterize its EDAC counters in future studies. Regarding the energy of the particles needed to trigger an EDAC event at Mars Express, Ramstad et al. (2018)

identified that the particles that produce ASPERA-3 background solar detections are electrons with energies >1 MeV and protons >20 MeV. After considering the study cases of this work and on a first approximation, we get an estimate that particles (most likely penetrating protons) with minimum energy of the order of 20-40 MeV are responsible for solar particle events that trigger the EDAC counters at Mars Express. However, we note that the minimum flux is needed at high energies to trigger an event is not clear as yet and requires further investigation.

5. Conclusions, Recommendations and Future Work

In this feasibility study, we have demonstrated that this technique can provide highly valuable data to examine the occurrence and propagation of SEP events, in particular when dedicated instrumentation is not available. However, dedicated instrumentation should be considered as a standard for missions, in particular deep space, as humanity reaches further from Earth. We have used EDAC counters from seven ESA spacecraft, including Venus Express, Mars Express, ExoMars-TGO, Rosetta, BepiColombo, Solar Orbiter and Gaia, as well as EDAC counters from the SWA-HIS instrument onboard Solar Orbiter.

We have shown that:

- Moderate to large SEP events in terms of flux and energy can trigger an EDAC detection.
- The same SEP event could be registered with EDAC counters at different and well-spread locations in the inner Solar System and at very far angular and radial distances. This indicates that the EDAC counters of this study could be used for future events as scientific data in the inner Solar System, with the caveat that we have not tested their response within Earth magnetosphere yet.
- We discuss that the EDAC sudden rises in memory errors could be mainly caused by protons of different energy levels depending on each spacecraft shielding and memory sensitivity. However, to get a final conclusion, the actual shielding of the spacecraft is needed (which is not available at the moment).
- Any spacecraft can act as an EDAC-SEP monitor, including those with no-solar science or planetary purposes as was highlighted by EDAC observations from Gaia.
- Mars Express seems to be the most sensitive to SEP events. Based on this work, protons with minimum energy of the order of 20-40 MeV seem to be responsible for solar particle events that trigger the EDAC counters of Mars Express. It is also the older mission in operation used in this work, which means that the technologies used are different.

Because of the evident usefulness of data from spacecraft EDAC counters, we strongly recommend:

- To make these housekeeping data available to researchers, especially those that have been properly identified as sensitive to SEPs and GCRs.
- For new and upcoming missions, all relevant sensors, shielding spacecraft models should be made available (at least, a reduced CAD model including the shielding and material properties)
- We recommend to cross-check with known spacecraft operation times to avoid false positives if EDAC data are to be used in a scientific study.
- To calibrate in a laboratory the response of EDAC to radiation doses, e.g., to test the threshold needed to trigger SEUs, SEFIs and other errors in EDACs.

More work is needed in order to fully characterize the EDAC response at each spacecraft. Our future plans include:

- A more exhaustive analysis of the Mars Express dataset as it has a good temporal resolution and has the largest continuous coverage in the Solar System. Thus, we can get a better characterization of the effects of solar activity on the responses.
- Other Earth-based EDAC observations will be characterised with specific instrumentation such as SOHO/ERNE that provides proton energy channels from 51-100 MeV.
- BepiColombo and Solar Orbiter will be revisited once larger SEP fluxes are available in the ongoing solar cycle 25.
- ESA's Jupiter Icy Moons Explorer (JUICE) (Grasset et al., 2013) cruise EDAC observations will be considered in future work.
- Other parameters/sources will be explored in order to understand what else could be detected with these sensors, such as Forbush decreases (i.e., ICMEs), shocks, CIRs, Jupiter particles on Mars' orbit, etc.

Acknowledgements

B.S.-C. acknowledges support through STFC Ernest Rutherford Fellowship ST/V004115/1 and STFC grant ST/Y000439/1. Moreover, the ESA Archival Research Visitor Programme is gratefully acknowledged for the opportunity to perform this activity and discuss with the different people involved in all these ESA missions during two visits at ESTEC. The ESA Science Faculty - Funding reference ESA-SCI-SC-LE-134 is also acknowledged. M.L. acknowledges support through STFC grant ST/W00089X/1. D.M. acknowledges support through the undergraduate summer bursary program of the Royal Astronomical Society (summer 2021), and from a PhD Studentship supported via the University of Leicester's Future-100 Scholarship scheme. E.W.K and S.V acknowledges financial support from CNRS/LATMOS to contribute to this work. S.J. acknowledges support from ESA contract

RFP/3-17233/21/ES/JD. D.H. was supported by the German Ministerium für Wirtschaft und Klimaschutz and the German Zentrum für Luft- und Raumfahrt under contracts 50QW1501, 50QW2202 and 50QJ1501. We acknowledge the European Union’s Horizon 2020 research and innovation program under grant agreement No. 871149 for Mars Express and Venus Express ASPERA3-4 background data. Solar Orbiter is a mission of international cooperation between ESA and NASA, operated by ESA. The rest of the missions from which EDAC data have been used are operated by ESA.

Open research (availability statement)

EDAC data used to produce the figures of this paper are available at Sanchez-Cano et al., (2023b). Other Mars Express, Venus Express, Rosetta and BepiColombo data are available at the ESA Planetary Science Archive (https://archives.esac.esa.int/psa/). Solar Orbiter data are available at the ESA Solar Orbiter Archive (https://soar.esac.esa.int/). Mars Odyssey and MSL data are available at the NASA Planetary Data System (https://pds.nasa.gov/). The OMNI dataset was downloaded from https://omniweb.gsfc.nasa.gov/ .

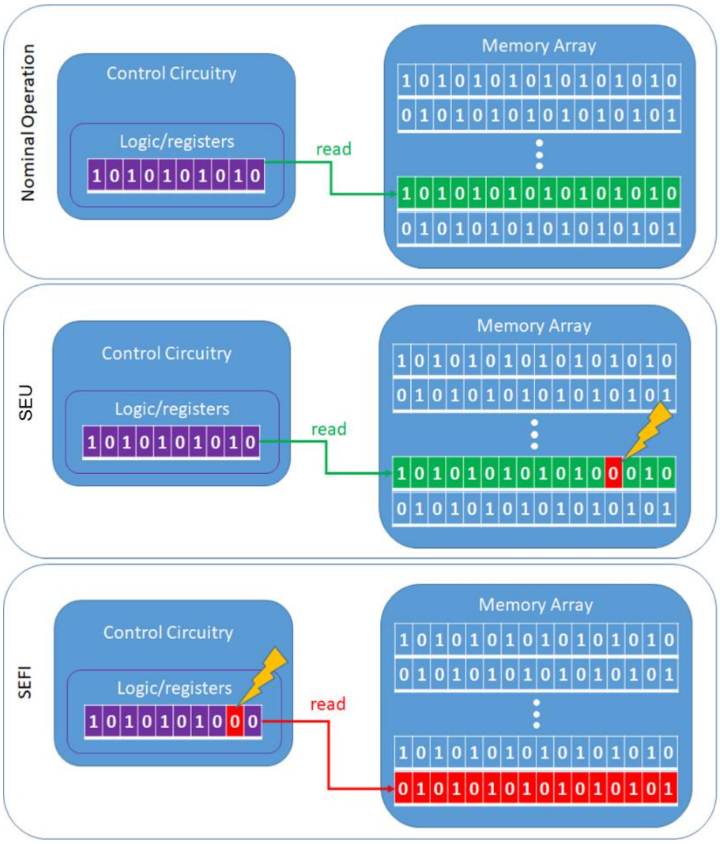

Figure 1: Diagram showing the effect of a Single Event Upsets (SEUs) and Single Effect Functional Interrupts (SEFI) on memories. Memories have a control circuitry which is responsible for all memory operations including reading the correct address in the memory array. (Top panel) During normal operation, the control circuitry correctly reads the memory arrays which have no errors. (Middle panel) If a SEU occurs, i.e., if a particle hits a memory cell in the memory array, the cell will change status. While the control circuitry will still read the correct address, an error in one of the bits will be caught by the Error Detection And Correction (EDAC) function (if implemented). The error is then corrected by writing the cell back to its previous status. (Bottom panel) A SEFI occurs when a particle hits the logic/registers in the control circuit. In this case, different effects can happen depending on which register is affected. One potential effect is that the wrong row will be read (Guertin et al., 2012). Depending on the memory content, EDAC counters might find errors in each cell location, resulting in a large number of errors which can be misidentified as the impact of Solar Energetic Particles.

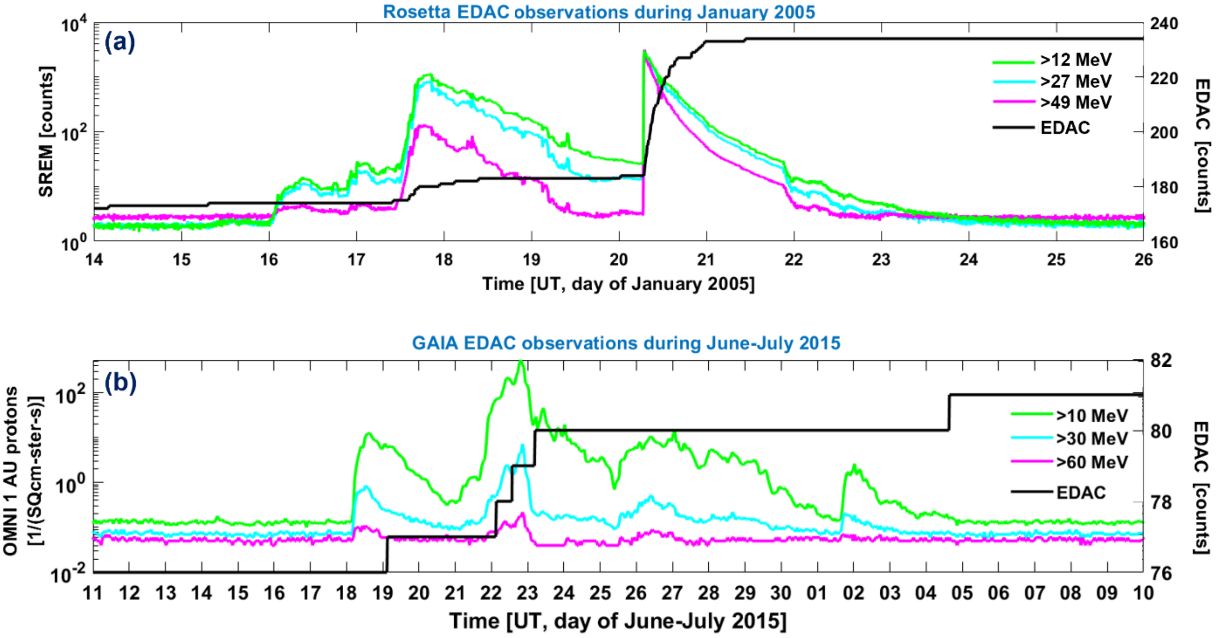

Figure 2: EDAC observations (black profiles, right Y-axis) together with solar particle event observations at the same location (energy bands in colors, left Y-axis), for two different events observed by Rosetta at 1.07 au (a) and Gaia (b). The solar energetic particles in (a) are protons measured by SREM at Rosetta and in (b) are protons obtained from the OMNI dataset at 1 au.

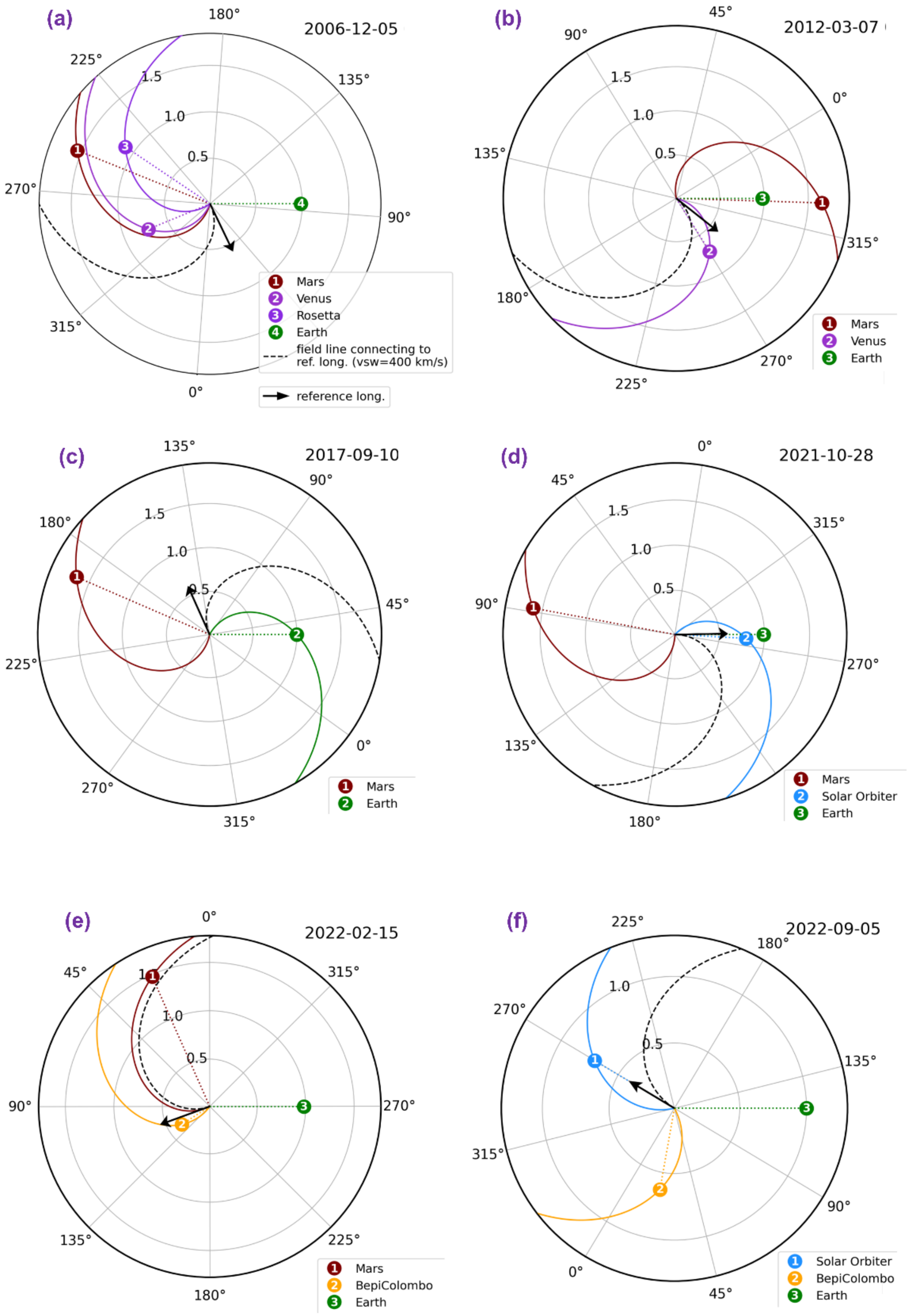

Figure 3: Planet and spacecraft positions (as indicated) for the six events of this work together with the Parker Spiral crossing each body for solar wind speeds of 400 km/s. Radial distances of each body are indicated in astronomical units (au), and angular information is given in Carrington longitude. Earth is located at 3 o`clock in each plot. The flare of reference of each event is indicated with a black arrow. This figure has been created with the Solar-MACH tool (Gieseler et al., 2023).

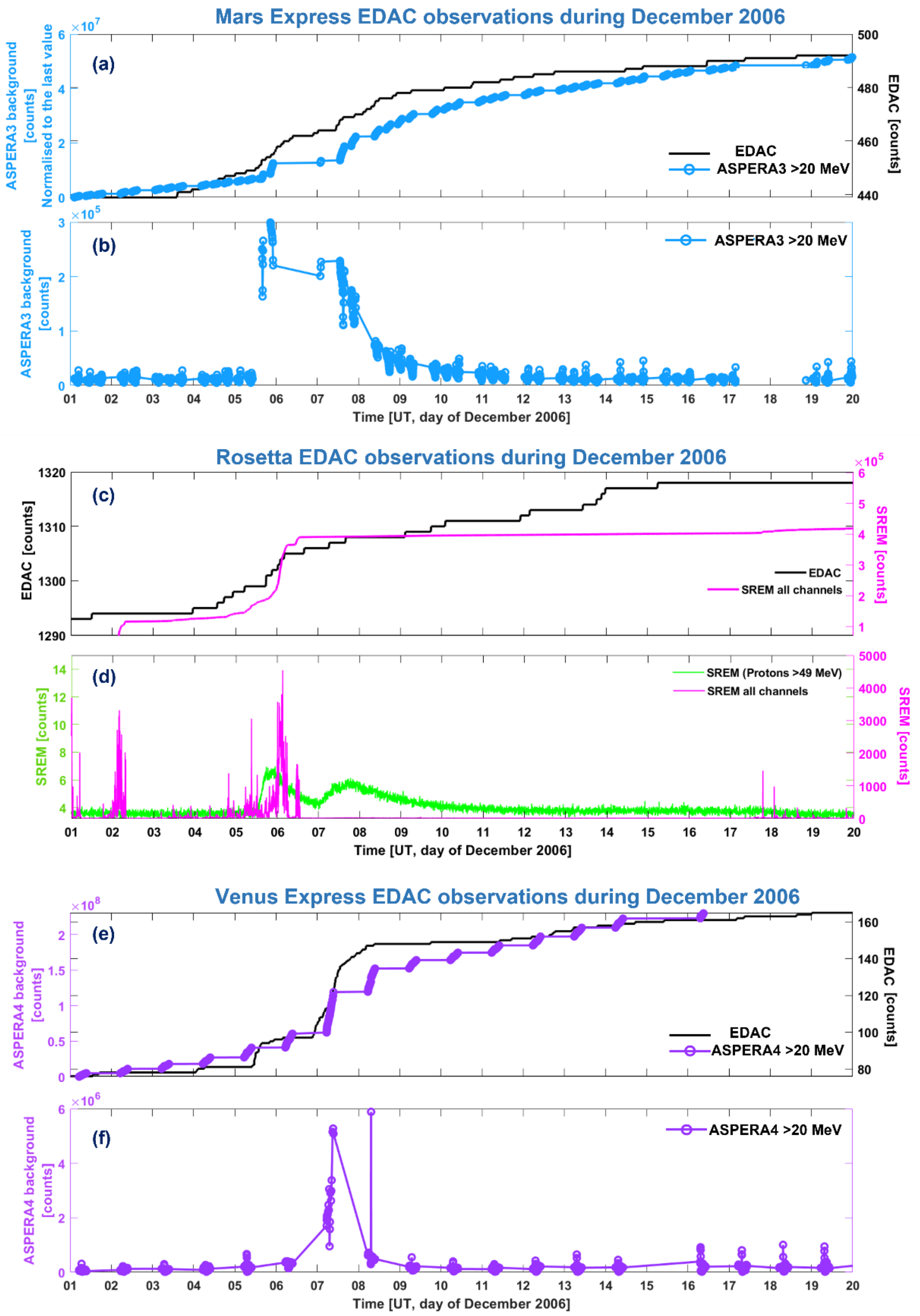

Figure 4: Solar particle event in December 2006. (a, b) Mars case. Mars Express (black) EDAC observations together with cumulative sum (a) and count observations (b) of the solar particle event by ASPERA-3-Mars Express (light blue). (c, d) Rosetta case. Rosetta EDAC observations together with cumulative sum (c) and flux observations (d) of the sum of all Rosetta-SREM channels. SREM observations of protons with energies >49 MeV are plotted in green in panel (d), but not in (c) due to

the low statistics of this channel. (e, f) Venus case. Venus Express (black) EDAC observations together with cumulative sum (a) and count observations (b) of the solar particle event by ASPERA-4-Venus Express (purple).

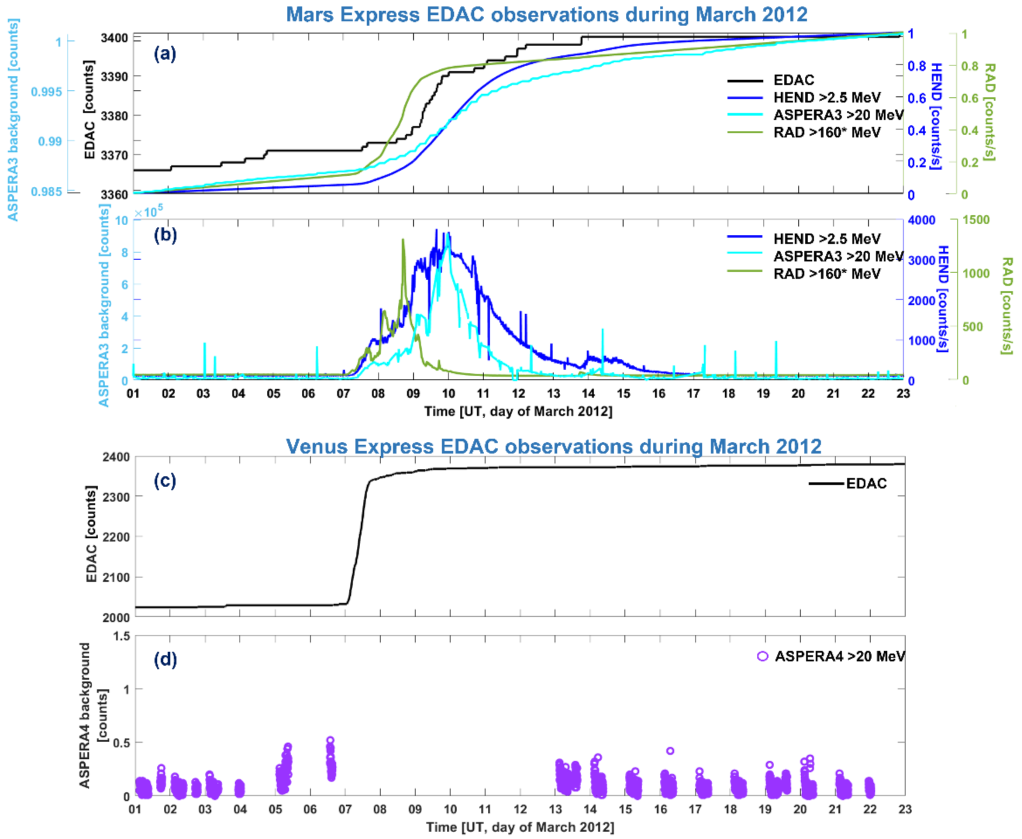

Figure 5: Solar particle event in March 2012 (a, b) Mars case. Mars Express (black) EDAC observations together with cumulative sum (a) and count observations (b) of the solar particle event by ASPERA-3-Mars Express (light blue), HEND-Mars Odyssey (dark blue) and MSL-RAD (green). (c) Venus case. Venus Express (black) EDAC observations, and (d) ASPERA-4-Venus Express (purple). HEND, RAD and ASPERA3 observations in panel (a) have been normalized to the last value to help the comparison.

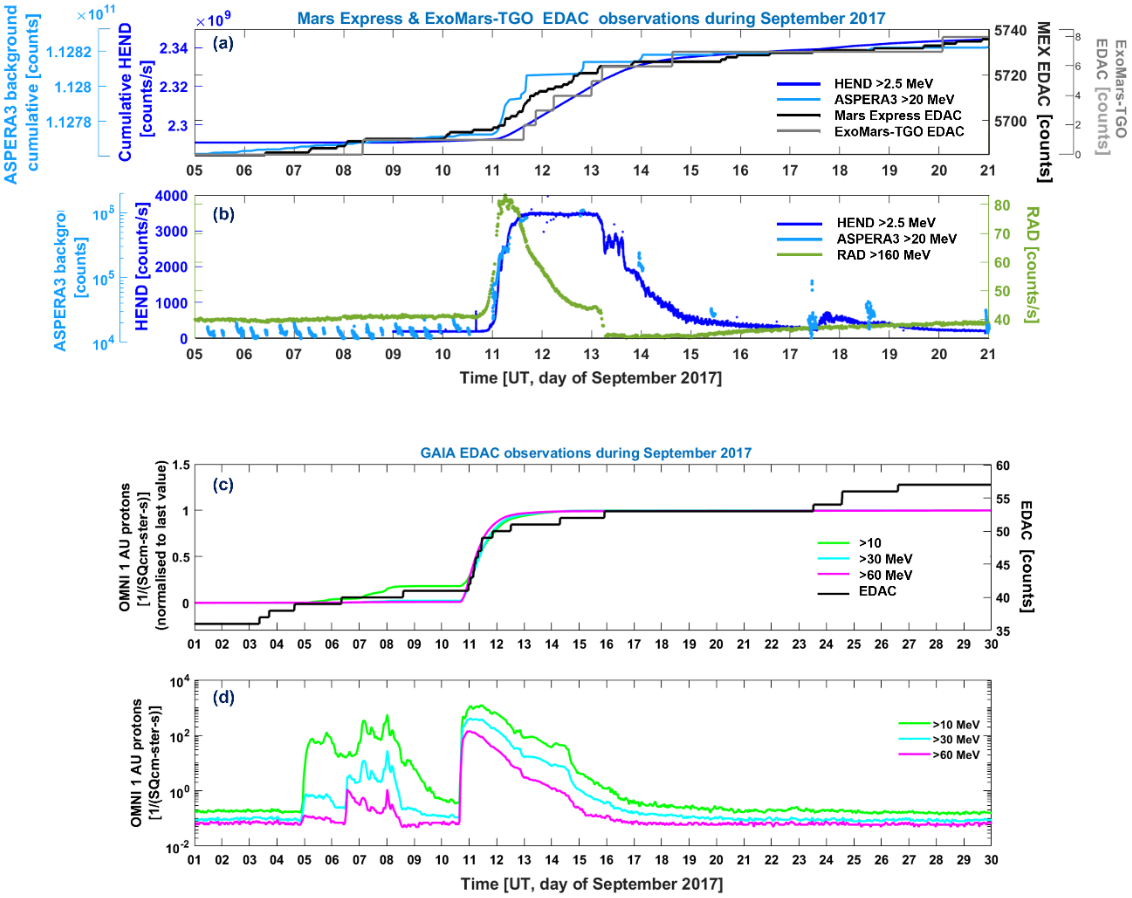

Figure 6: Solar particle event in September 2017. (a, b) Mars case. Mars Express (black) and ExoMars-TOG (grey) EDAC observations together with cumulative sum (a) and count observations (b) of the solar particle event by ASPERA-3-Mars Express (light blue, y-axis in log-scale in panel b only) and HEND-Mars Odyssey (dark blue) in orbit, and RAD-MSL at the surface of Mars (green). (c, d) Earth case. Gaia EDAC observations at L2 (black) together with cumulative sum (c) and flux observations (d) of three different energy bands of the solar particle event recorded at the OMNI dataset at 1 au (note y-axis in log-scale).

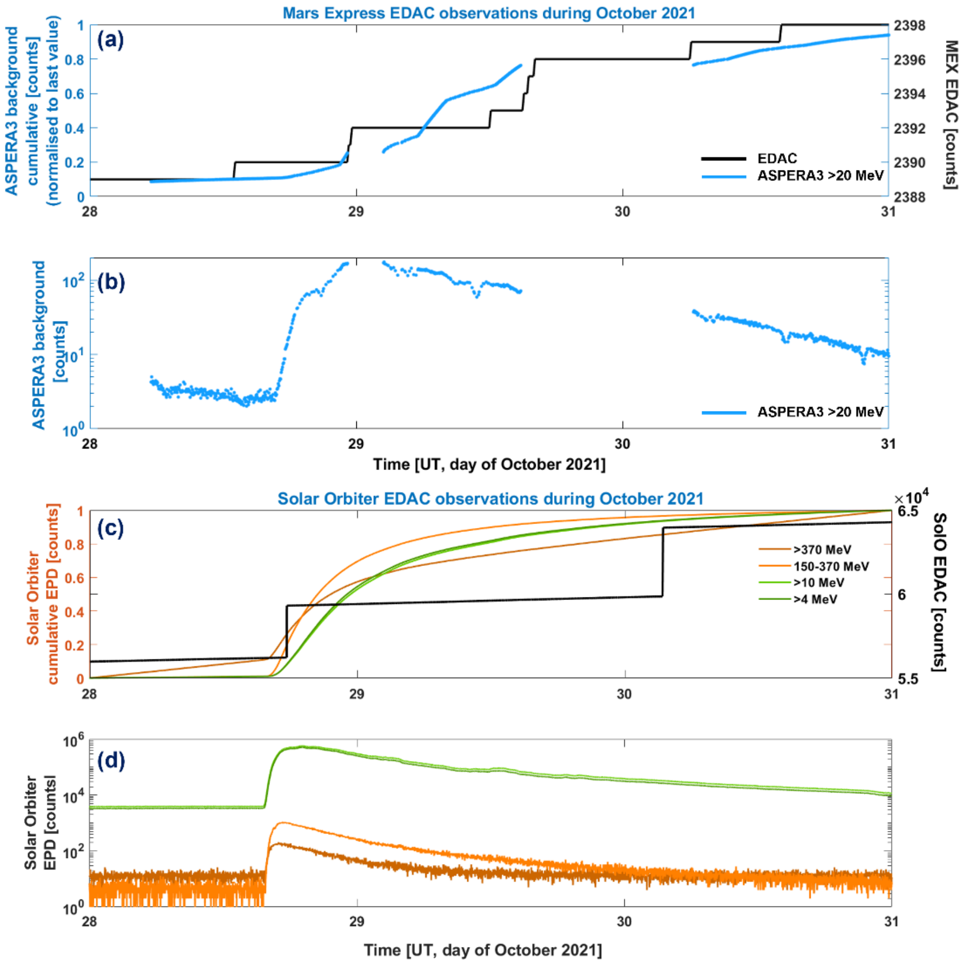

Figure 7: Solar particle event in October 2021. (a, b) Mars case. Mars Express EDAC observations (black) together with cumulative sum (a) and count observations (b) of the solar particle event by ASPERA-3-Mars Express (blue curve). (c, d) Solar Orbiter case. Solar Orbiter EDAC observations together with cumulative sum (c) and count observations (d) of the solar particle event recorded by the same mission. This is a NON-event in EDACs.

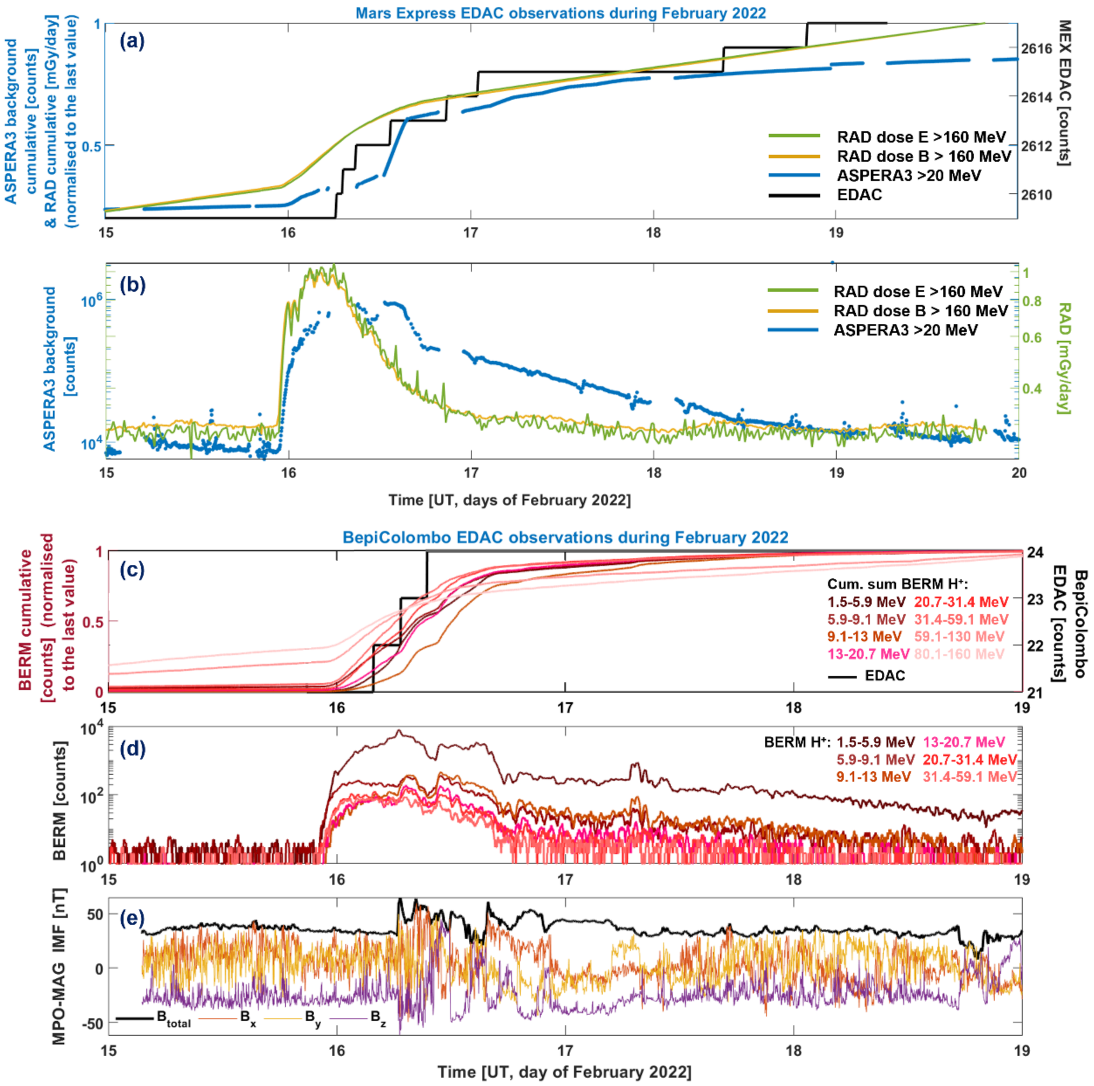

Figure 8: Solar particle event in February 2022. (a, b) Mars case. Mars Express EDAC observations (black) together with cumulative sum (a) and count observations (b) of the solar particle event by ASPERA-3-Mars Express (blue) and MSL-RAD (green and yellow). (c-e) BepiColombo case. BepiColombo EDAC observations together with proton cumulative sum (c) and count observations (d) for different energy ranges, and magnetic field (e) recorded by the same mission.

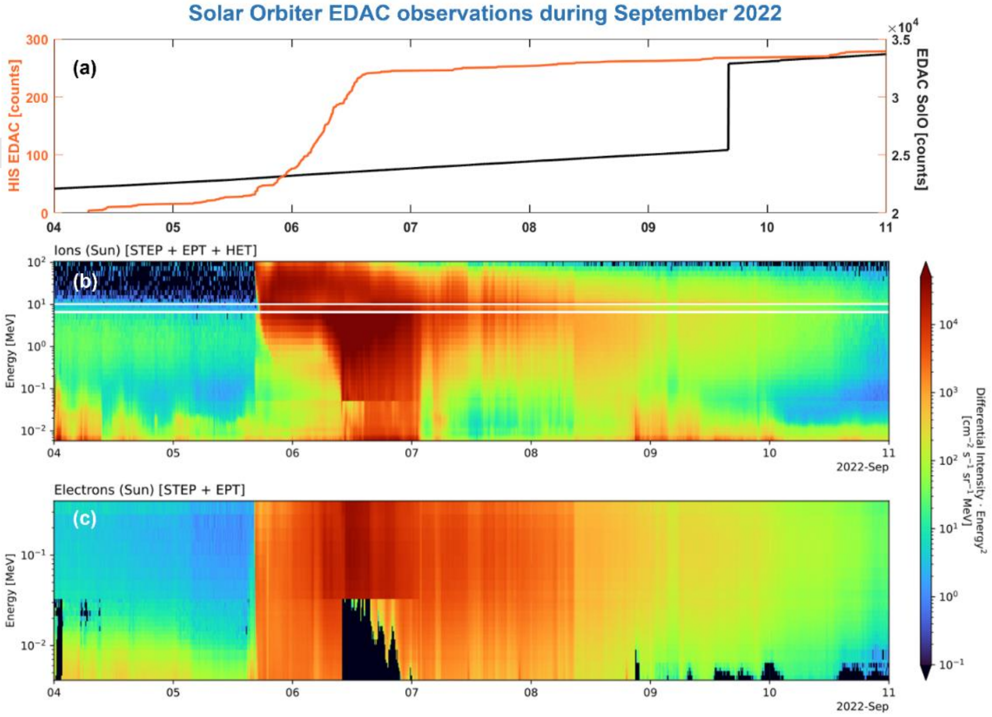

Figure 9: Solar particle event in September 2022. Solar Orbiter case. (a) Solar Orbiter EDAC observations (black) together SWA-HIS EDAC observations (orange). (b) EPD ion spectra quicklook plot from https://espada.uah.es/epd/data/plots/quicklook. (c) same as (b) but for electrons.

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