Galactic Cosmic Rays at Mars and Venus: Temporal Variations from Hours to Decades Measured as the Background Signal of Onboard Microchannel Plates

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Abstract

A microchannel plate (MCP) is a component widely used for counting particles in space. Using the background counts from MCPs on the Mars Express and Venus Express orbiters—operating over 17 yr and 8 yr, respectively—we investigated the galactic cosmic ray (GCR) characteristics of the inner solar system. The MCP background counts at Mars and Venus, on a solar cycle timescale, exhibited clear anticorrelation with the sunspot number. We concluded that the measured MCP background counts contained GCR information. The GCR characteristics measured using the MCP background counts at Mars showed features consistent with measurements on Earth in Solar Cycle 24. The time lag between the sunspot number and the MCP background counts was found to be ~9 months at Mars. The shorter-term background data recorded along the orbits (with a timescale of several hours) also showed evident depletion of the background counts, due to absorption of the GCR particles by the planets. Thanks to the visible planetary size change along an orbit, we developed a model to separate the GCR contribution to the MCP background counts from the internal contribution caused by the $\beta$-decay of radioactive elements in the MCP glass. Our statistical analysis of the GCR absorption signatures at Mars implies that the effective absorption radius of Mars for the GCR particles is $>100$ km larger than the radius of the planet. However, the cause remains an open question.

Unified Astronomy Thesaurus concepts: Galactic cosmic rays (567); Mars (1007); Venus (1763); Planetary atmospheres (1244); Cosmic ray detectors (325)

1. Introduction

Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) contribute to the high-energy particles that are a threat to human activities in space. Robotic missions suffer electronics failures because of these high-energy particles. Humans in space also suffer damage to their deoxyribonucleic acid (DNA). Therefore, monitoring high-energy particles, such as GCRs and SEPs, is critical to enabling space exploration, and the characterization of such particles has been of significant interest to the space weather community. Because deep-space cruising, such as travel to the Moon or Mars, is foreseeable in the future, there is an increasing necessity to obtain an understanding of the high-energy particle radiation environment in interplanetary space and around extraterrestrial planets.

High-energy radiation also impacts the biological environment in planetary atmospheres and on surfaces and subsurfaces. Measurements and investigations of the radiation environment have implications for the past (or present) life in the solar system. Such knowledge could provide insights into the habitability of exoplanets (Jasinski et al. 2020). Several investigations on GCRs, both through modeling and measurement, have been conducted on the solar system, including on Mercury (Lawrence et al. 2016), the Moon (Spence et al. 2010; Dachev et al. 2011), and Europa (Nordheim et al. 2019).

On the Martian surface, the Radiation Assessment Detector (RAD) instrument has been operating since 2012 (Hassler et al. 2012, 2014), and a wealth of relevant data sets have been recorded. The GCR signatures in these data sets have shown similar characteristics to those measured on the Earth, such as an anticorrelation with the sunspot number (Forbush 1958; Guo et al. 2021). Shorter-term variations, caused by interplanetary coronal mass ejections (ICMEs)—referred to as Forbush decreases—have also been identified (Winslow et al. 2018). Conversely, experimental data obtained from the vicinity of Venus is limited. However, GCR particles are considered to play a significant role in the ionization of the lower atmosphere (∼70 km), where there is a possibility of a habitable zone (Nordheim et al. 2015).

In this study, we investigated temporal variations in GCR intensity using the background counts measured by microchannel plates (MCPs) operating near Mars and Venus over the course of 17 yr and 8 yr, respectively. It is well-known that high-energy particles provide MCP background counts; for example, SEPs produce this type of background counts (Futaana et al. 2008; Ramstad et al. 2018). Using the same principle, it is possible to record GCRs as MCP background counts. Here, we show that MCP background counts contain information on GCR particles close to planetary bodies (Venus and Mars). We also discuss the temporal variations over different timescales—from hours to decades—based on the data sets obtained by the orbiters around Venus and Mars.

2. Microchannel Plate Background Sources

An MCP is a component widely used for counting photons and particles (Carlson & McFadden 1998). MCPs have wide effective areas and high precision for determining the positions of incoming particles hitting the plate. However, background...
counts are unavoidable (Sieg mund et al. 1988). In this section, we briefly overview the characteristics of MCP background sources.

High-energy particles are notable contributors to MCP background counts. Even though MCPs are usually located deep inside space instrumentation, high-energy particles can still penetrate the instrument wall and directly access the MCP. Some particles stochastically collide with atoms inside the MCP lattice, producing a background signal. A minor portion of the MCP background signal can be caused by secondary species (including photons) resulting from the impact of primary high-energy particles on the structures of the instrument and spacecraft. In space, the main contribution is from SEPs and GCRs. Electrons from the Jovian magnetosphere add a minor contribution to the background counts (Krimigis et al. 1975). In addition, radiation sources from space vehicles (e.g., radioisotope thermoelectric generators or radioisotope heater units) can also produce MCP background counts.

SEPs are electrons and protons accelerated by the shock waves formed by solar flares, ICMEs, and corotating interaction regions (CIRs). These particles can typically reach MeV-level energies (e.g., Reames 1999; Ryan et al. 2000). In most cases, SEP fluxes are abruptly increased by several orders of magnitude when an ICME or CIR arrives at a spacecraft location. The time series of the MCP background counts have been found to show similarities to general trends in SEP intensity. Therefore, we have been using the MCP background counts as a space weather monitoring tool through the heliosphere (Futaana et al. 2008; Ramstad et al. 2018; Palmero et al. 2021).

Another population of high-energy particles in space comes from GCRs, which mostly derive from outside the solar system, mainly in the Milky Way. They are thought to be created by supernova explosions (Simpson 1983). A small portion of GCRs may have been produced in other galaxies (Aab et al. 2017). They usually have higher energy than SEPs, peaking at several hundreds of MeV to several GeV, and are mainly proton and alpha particles, with minor contributions of high-mass species.

It is well-known that a clear solar cycle modulation (anticorrelation) exists between GCR intensity and the solar cycle (Van Allen 2000; Potgieter 2013). This modulation is caused by the different states of turbulence in the solar system as a function of solar activity, resulting in GCR transport disturbances (Parker 1965; Fisk 1971; Caballero-Lopez & Moraal 2004). Geomagnetic disturbances called Forbush effects, caused by magnetic storms, also modulate GCR intensity at the ground on shorter timescales (Forbush 1938). Recently, Forbush effects have been recorded at the Martian surface, driven by the passages of ICMEs (Winslow et al. 2018; Guo et al. 2021). These Martian Forbush effects have been found to correlate highly with events on the Earth (Papaioannou et al. 2019).

Regardless of the source of the high-energy particles, deriving their absolute intensity or the shape of their energy spectra from MCP background data is generally not straightforward. Assuming an energy spectrum of high-energy particles (the differential flux, with the units in cm$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{-1}$), $j(E, \Omega)$, the background counts ($C$) are expressed as

$$C = \int \int j(E, \Omega) P(E, \Omega) dE d\Omega,$$  

where $P(E, \Omega)$ is the number of counts produced when a single high-energy particle hits the MCP. This is a function of the energy, $E$, coming from direction $\Omega$. Because we can only determine the integrated value of $C$ from the background measurement in space, deconvolution is needed to derive the differential flux. This is a typical inversion problem in an underdetermined system. A further complication comes from the fact that we have no information about $P(E, \Omega)$. Theoretically, $P(E, \Omega)$ is nonlinear in energy. It also depends on the materials surrounding the MCP, as well as the geometry of the instrument and the spacecraft. Background counts can also be produced by secondary particles.

The $\beta$-decay of radioactive elements in MCPs is another strong background source. Through this process, MCPs produce signals without interacting with particles in space. The internal sources are from radioactive elements in the MCP glass. When a radioactive element decays, electrons are emitted inside the MCP, causing electron avalanches and producing background counts. The most significant contributor is $^{40}\text{K}$, with a half-life of $\sim$10$^6$ yr. Thus, the contribution should be constant over a temporal scale of 10 yr in this study. Previous studies (e.g., Siegmund et al. 1988) have reported that the typical MCP background event rate was $\sim$0.1 cm$^{-2}$ s$^{-1}$.

Several other processes can result in background counts. Siegmund et al. (1988) explained that outgassing from an MCP can do this, as well as a hotspot produced by a dust particle on the MCP. However, these contributions are presumably minor for space instrumentation, because the sensors are baked and cleaned adequately before launch. After launch, the instruments operate in a high-vacuum environment.

UV photons are an additional possible source of background counts. However, the UV contribution is generally less critical because MCPs are located inside the instrument chassis, and photons should collide with properly coated walls several times before reaching the MCPs.

3. Instruments and Data

We used data sets obtained by the European Space Agency’s (ESA’s) planetary missions—Mars Express and Venus Express. Mars Express was launched in 2003 with the aim of exploring the red planet (Chicarro et al. 2004). The Mars Express spacecraft has been inserted into a Martian orbit (with a pericenter of $\sim$250 km and an apocenter of $\sim$10,000 km, both measured from the surface of Mars). The mission is still in operation (as of 2022), orbiting around Mars, with further continuous operation expected. Measurements taken over the course of 17 yr from a Mars orbit provided a unique data set, helpful in understanding our neighboring planet and the space environment around it.

Venus Express was launched in 2006 with the aim of exploring our twin planet, Venus (Svedhem et al. 2007). It was initially inserted into a highly elliptical polar orbit (with a nominal pericenter altitude of $\sim$200 km), but later, the pericenter was lowered to 135 km (Müller-Wodarg et al. 2016). Venus Express was operated until the end of 2014, by which time the spacecraft had consumed the entirety of the fuel that enabled it to maintain its orbit. However, there is more than 8 yr worth of data available from the orbit around Venus, which we were able to use in this study.

Among the many scientific instruments on board Mars Express and Venus Express, two space plasma instruments, the Analyzers of Space Plasma and Energetic Atoms (ASPERA-3 and ASPERA-4), were carried to Mars and Venus (Barabash et al. 2006, 2007). These sensors were based on a common
design, but were tailored to each environment. These instruments have been used to reveal the solar wind interaction with nonmagnetized planetary atmospheres. A specific focus has involved quantifying atmospheric escape in the form of charged particles (Futaana et al. 2017). In addition to the charged particle measurements, the first-ever remote sensing of the plasma environment was conducted by measuring energetic neutral atoms (ENAs; Futaana et al. 2011).

In this study, we used the Ion Mass Analyzer (IMA) sensor of the ASPERAs. The maximum energy that can be measured by an IMA is $\sim 36 \, \text{keV} \, \text{q}^{-1}$. While no high-energy plasma data were available, because these missions were not designed to investigate high-energy plasma physics, we were able to use the IMA background counts to qualitatively assess the SEP fluxes at Mars and Venus (Futaana et al. 2008; Ramstad et al. 2018). Through an inter-comparison with the high-energy particle data obtained from the Mars Atmosphere Volatile EvolutionN (MAVEN) mission, Ramstad et al. (2018) experimentally derived a threshold of the contributing particle energy for the IMA background counts. They concluded that the main contributions were from electrons with $>1 \, \text{MeV}$ and protons with $>\sim 20 \, \text{MeV}$. This is equivalent to the $\sim 2 \, \text{mm}$ thick Al shielding (NIST 2017).

Figure 1(a) shows a cross section of the IMA sensor. The IMA sensor uses a standard ion optics design to analyze the energy, mass, and incoming direction of the ions (Barabash et al. 2006, 2007); an electrostatic deflection system to select the elevation angle (the angle with respect to the aperture in the top-hat electrostatic analyzer), an electrostatic analyzer (ESA) for energy filtering, and a velocity analyzer based on a permanent magnet system. The ions are counted using a detection system comprising two-stacked MCPs (biased by $-2800 \, \text{V}$) with a 100 mm diameter (Figure 1(b)). The impact point of an ion on the MCP depends on its mass, energy, and incoming direction. The MCP produces $\sim 10^5$–$10^6$ electrons, fed to a position-detection system behind the MCP, which provides the information on impact position with 32 radial (rings) and 16 azimuthal (sector) resolutions using six preamplifiers and an FPGA-based coincidence algorithm. Overall, a four-dimensional (4D) histogram of the counts (mass, energy, azimuth angle, and elevation angle) is provided every 192 s.

The time series of a 4D histogram was the starting point for this study. We then reduced the histogram to 2D (i.e., an energy–mass histogram) by collapsing the information about the directions. To illustrate the statistical features of the IMA’s performance, Figure 2 is provided as an example of an energy–mass histogram for the data accumulated over the course of one month. The number of mass bins is 32, and there are 96 energy bins. The corresponding foreground ion energy is shown on the right. The horizontal axis represents the mass ring number. The white curves represent the mass per charge of the foreground ion and the energy for the IMA background counts. They concluded that due to substantial interference. The background counts were spread over all of the energy and mass bins. The orange boxes indicate the background channels.

**Figure 1.** (a) Cross section of the Ion Mass Analyzer (IMA) instrument showing four main sections—electrostatic deflector, electrostatic analyzer (ESA), magnets, and microchannel plate (MCP). The Digital Processing Unit (DPU) is the processing unit of the IMA (Barabash et al. 2006). The orange curve indicates a typical ion trajectory moving through the instrument, recorded as a foreground count. (b) MCP used for the Mars Express IMA, with a diameter of 10 cm.

**Figure 2.** (a) Mars Express and (b) Venus Express IMA counts accumulated over 1 month (2008 January) represented in an energy–mass matrix. There are 96 energy bins. The corresponding foreground ion energy is shown on the right. The horizontal axis represents the mass ring number. The white curves represent the mass per charge of the foreground ion and the energy (proton, alpha, oxygen ions, and other positive ion species). Mass bins 0, 4, 10, and 23 for Mars Express were disabled due to substantial interference. The background counts were spread over all of the energy and mass bins. The orange boxes indicate the background channels.
The mass bin index corresponds to the radial position of the MCP (ring). The energy bin index number corresponds to the physical energy per charge (indicated on the right axis). Depending on the actual mass per charge and the actual energy, the foreground ions appear in specific areas in the energy–mass plot, as represented by the white curves in Figure 2.

The background counts are visible as a spread of constant counts over the whole energy–mass bins. On top of the background counts, the foreground signal can be clearly seen as clusters of counts. For example, the solar wind protons, with energies of 0.5–2 keV \(q^{-1}\), are visible along the \(M/Q = 1\) curve on the mass ring numbers \(>25\) in the Mars Express data (Figure 2(a)). A weaker signal at \(M/Q = 2\) (solar wind alpha particles) can also be seen at \(1–4\) keV \(q^{-1}\). The ionospheric ions from Mars can be found at the lowest energy, in the 8–15 mass bins. The depletions visible at specific mass ring numbers (0, 4, 11, and 22) are artificial. We disabled those mass bins on board, due to substantial interference in the position-detection system (front-end electronics). Electronics interference can also cause a moderate dependence of the detection efficiency on mass bins; for example, the background signals for mass bins 16, 20, 24, and 26 are higher than those for the neighboring bins. Improvements in the front-end electronics for Venus Express IMA led to better performance in terms of the detection efficiency dependence on the mass channel (Figure 2(b)). Of course, foreground ions (solar wind protons and alpha particles and Venusian ionospheric ions) are easily identifiable in the Venus Express data as well.

Because the \(M/Q\) of any ion species is limited to \(\geq 1\), no foreground ions can reach the upper right corner areas in the energy–mass plots (Figure 2). We took that region as the background channel. The optimal background channel for the Mars Express IMA involved the mass bins 27–30 and the energy steps 1–11. For the Venus Express IMA, the mass bins 25–30 and the energy steps 1–12 were used (Capalbo 2010).

We took the sum of the counts inside the background channel to derive the background counts. The summed background counts (every 192 s) were then divided by the number of background bins (44 for Mars Express and 84 for Venus Express), producing the raw background count data \(B_{\text{MEXRAW}}\) and \(B_{\text{VEXRAW}}\).

These background counts are highly related to the instrument design, and it is not straightforward to convert them into physical quantities (e.g., background count rate per area). Due to a lack of information and calibration data, the effective areas of the MCP could only be slightly constrained. Our simple estimation provided \(\sim 18\) and \(\sim 27\) cm\(^2\) as the effective areas corresponding to the background channels for Mars Express and Venus Express, respectively. The effective duration of the measurements was 22 s for Mars Express and 28 s for Venus Express during the cadence of 192 s. Overall, the background count rate per MCP area could be calculated from the raw background count values:

\[
B_{\text{MEX}}[\text{cm}^{-2}\text{s}^{-1}] \sim 0.11 \times B_{\text{MEXRAW}},
\]

\[
B_{\text{VEX}}[\text{cm}^{-2}\text{s}^{-1}] \sim 0.11 \times B_{\text{VEXRAW}}.
\]

However, we kept the raw background count values for this study (unless otherwise noted) in order to avoid giving the impression that the numbers shown have been well-calibrated.

### 4. Decadal Variations

In this section, the long-term trends in the IMA background counts are described to discuss an 11 yr solar activity cycle. Figure 3 shows the time series of the background data. The median values of the background counts for every three months are shown. The typical number of IMA scans was \(\sim 10,000\) within each three-month window. In addition to the median, the 5%, 25%, 75%, and 95% percentiles are also indicated in Figure 3. By taking the median, we could minimize the influence from SEP events because intense SEP fluxes only last for approximately a week.

The Mars Express IMA background counts were 1–3 per scan, corresponding to \(\sim 0.1–0.3\) cm\(^2\) s\(^{-1}\) (Equation 2). The Venus Express IMA background counts were 6–8 per scan, corresponding to \(\sim 0.7–0.9\) cm\(^2\) s\(^{-1}\) (Equation 3). The expected nominal background count rates of 0.1 cm\(^2\) s\(^{-1}\), caused by the \(\beta\)-decay for typical MCPs and the GCR contribution at ground level, were actually 0.1–0.5 cm\(^2\) s\(^{-1}\) (Siegmund et al. 1988). All these values were within the range of the IMA background count rates.

A distinct signature is visible in Figure 3—a clear trend of anticorrelation between the sunspot number (Figure 3(c)) and the IMA background counts (Figure 3(b)). This anticorrelation is consistent with the GCR characteristics for Earth, the intensities of which are known to anticorrelate with solar activity (e.g., Van Allen 1993, 2000). This modulation has also been measured at the Martian surface by RAD (Guo et al. 2021). We can thus conclude there is a substantial contribution of GCR intensity to the MCP background counts at Mars.

The anticorrelation to the sunspot number is less visible in the Venus Express IMA background data (Figure 3(a)). In the first year (2006), the background counts showed a decreasing trend. This feature is probably due to the influence of outgassing. Space instruments continuously outgas in the extremely high-vacuum environment after launch (Säljö et al. 2010), even though they were baked out on ground. After 2007, there was a monotonous increase in the background counts as the sunspot number decreased. This increase looks consistent with the Mars Express IMA background count increase from 2007 to 2010. A distinct drop in the Venus Express IMA background counts after 2010 was caused by a change in onboard processing. We introduced an onboard background count subtraction scheme in order to increase the primary science outcome. Already in 2006, we knew that relatively high background counts had increased the load in the onboard IMA processing system, resulting in packet losses. To avoid these, the 4D matrix was rebinned originally from 16 to eight. The drawback was the low angular resolution in the data. In 2010, a background count subtraction scheme was introduced to replace the rebinning. The counts in all the bins were decremented by one on board. Therefore, the bins with a raw count of one were recorded as having zero counts, and the load on the system was significantly mitigated. As a drawback, the background counts were reduced considerably, as shown in Figure 3(a). Despite the significantly reduced background counts, the anticorrelation with the sunspot number was still visible (Figure 4). The high correlation coefficients \(R = -0.66\) and \(-0.83\) for the periods before and after introducing the background count subtraction scheme) confirm that the background data obtained by the Venus Express IMA contained information on GCR intensity at Venus.
It would be an exciting discussion to determine how much this GCR flux differs between Mars (1.5 au) and Venus (0.72 au). Honig et al. (2019) claimed that there was a 3% au$^{-1}$ gradient in the GCR intensity between 1 and 4.5 au. If we apply the decrease rate, only a couple of percent of decrease might be expected between Venus and Mars. However, comparing the absolute background count rates from the Mars Express and Venus Express IMAs is complex because the details of the implementation were not entirely identical. For example, the front-end electronics in these sensors were optimized to perform foreground (space plasma) measurements in different environments. The threshold settings and the sensor temperatures during operation were also different. In addition, because the high-energy particle measurements were not an objective of the mission or these sensors, we did not conduct any ground calibrations for high-energy particles. Therefore, the response of each MCP to high-energy particles is unknown. Furthermore, the housings of the MCPs (shape of the spacecraft and IMA sensor body) differ. In summary, we are unable to quantitatively discuss the difference between the Venus Express (∼0.7–0.9 cm$^{-2}$s$^{-1}$) and Mars Express (∼0.1–0.3 cm$^{-2}$s$^{-1}$) IMA background counts.

It is well-known that there is an anticorrelation between sunspot number and GCR intensity (Forbush 1958; Van Allen 1993). This anticorrelation is due to the diffusion of GCR particles resulting from turbulence in the heliosphere (Parker 1965; Fisk 1971). Interestingly, the signature of GCR intensity has been found to differ between odd- (Cycles 21 and 23) and even-numbered (Cycles 20 and 22) cycles (e.g., Van Allen 2000; Belov 2000). This difference can be explained by disparities in the large-scale polarity of the solar magnetic field. However, an exception has occurred recently in Cycle 24, which has a similar signature to the odd-numbered cycles (Ross & Chaplin 2019).

Figure 3. Time series of the background counts from the (a) Venus Express IMA and (b) Mars Express IMA. The dots represent the median values derived from all available data during the three months interval, regardless of the spacecraft position and attitude. The error bars indicate the 25% and 75% percentiles (black) and 5% and 95% percentiles (gray). For the Venus Express IMA, an onboard background count subtraction scheme was introduced in 2010, so the background counts became extraordinarily small after 2010. The blue stars represent the same data, but with an extended scale (right axis). (c) Monthly sunspot number provided by the World Data Center sunspot Index and Long-term Solar Observations (SILSO), Royal Observatory of Belgium, Brussels.
Here, we compare the Mars Express IMA background counts with a data set from the neutron monitor observed on Earth (76.5° N, 68.7° W). Neutron monitors have been widely used for GCR monitoring, because GCR particles produce neutron showers in the middle atmosphere. Figure 5 shows the hysteresis for the Mars Express background counts (1 yr median) and the neutron intensity measured at the Thule station compared with the sunspot number. Similar and consistent shapes are clearly visible.

Another interesting feature was a possible time lag in the Mars Express background counts versus the sunspot number (Figures 3(b) and (c)). The recovery of the GCR intensity appears to have been delayed after the peak in solar activity. From several previous studies (e.g., Kane 2014), time lags of ~10–12 months are known to exist for odd-numbered solar cycles, where even-numbered solar cycles generally show no time lags. The only exception identified is for Cycle 24, where a lag of ~4 months was reported using ground-based neutron monitors (e.g., Tomassetti et al. 2017; Ross & Chaplin 2019).

Recently, using the engineering parameter of the error detection and correction (EDAC) counters on Mars Express, Knutsen et al. (2021) derived a time lag of 5.5 months between GCR intensity and the sunspot number for the years 2005–2020 at Mars. This exceptional feature associated with Cycle 24 has been attributed to either the long solar minimum between Cycles 23 and 24 or the relatively low solar activity during Cycle 24.

Figures 6 and 7 illustrate the correlation coefficients between the Mars Express IMA background counts (three months median) and the time-shifted sunspot number (three months median).
average). Figure 6 shows the best correlation for the nine months of time lag, with a correlation coefficient of \(-0.86\). Figure 7 shows the data with the nine-month time lag. This is slightly longer than the previously reported four-month lag from the ground-based measurements and the lag of 5.5 months from the Mars Express EDAC counters. In fact, the nine-month lag is more consistent with that identified for the odd-numbered solar cycles (Ross & Chaplin 2019). The effective energy of GCR particles to produce the background counts may be different from that of generating ground-based or the EDAC counter observations, because the time lag depends on the GCR particle energy. Nevertheless, the correlation was high in general (\(<-0.7\)) (Figure 6). Due to the lack of Mars Express IMA background characterization, our results may not actually contradict previously published results. We emphasize that our results support the existence of a time lag for Cycle 24, indicating that this cycle was exceptional among the other even-numbered cycles, as has been shown in previous studies.

In summary, the Mars Express IMA background data show clear anticorrelation to the solar activity, with a time lag of nine months. We can conclude that the GCR intensity signatures are common at Earth (1 au) and Mars (1.5 au). We carried out a similar investigation using the Venus Express IMA background count data. However, the onboard background reduction scheme (Figure 4) made the long-term analysis significantly complicated. Because of the change in operation at a time of peak solar activity, the time lag analysis, unfortunately, did not produce meaningful results.

5. Orbital Modulation

In this section, we focus on the shorter-time modulation over several hours. A change in the GCR-induced count rate along an orbit can be expected, because the closer the spacecraft is to a planet, the larger the planet appears and the more GCR particles are absorbed by the planet. On the other hand, the internal counts, driven by the decay of radioisotopes, are constant because the half-lives are significantly long (e.g., \(>10^9\) yr). Thus, the influence of the external GCR source can be separated from the internal \(\beta\)-decay source by using the time series of the background counts.

We developed a simple model to represent the background counts in order to apply to the background data along the trajectory of the spacecraft over one orbit close to the pericenter. Our model assumptions were as follows:

1. The internal background is constant over one pass of the spacecraft (several hours).
2. The external source (GCR particles) is isotropic, and the characteristics (e.g., energy and flux) do not change over one pass.
3. The external source coming from the direction of the respective planetary body is entirely blocked.

The first assumption would be justified because of the long half-life of \(^{40}\)K, whereas the electronics in the detection system could contribute to modifying the constant count rate, possibly due to the temperature drift of the threshold. In our simple model, we were not able to consider these types of nonlinear effects.

Using the above assumptions, we first formulated the GCR-induced counts. From the isotropic GCR directional-differential flux (integrated over the energy) without planetary blockage, denoted as \(j\) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)), the background counts detected by a planar MCP, denoted \(dC\), contributed from a solid angle (d \(\Omega\)) can be calculated by

\[
dC = j S (n \cdot d\Omega) r(\theta, \varphi) = j S d\Omega \cos \theta \varepsilon(\theta, \varphi).
\]

Here, \(S\) is the area of the MCP (which is constant), \(n\) is the normal vector of the MCP, and \(\varepsilon\) is the response of the MCP to the GCR particles coming from a specific direction. The angle \(\theta\) is the polar angle between the normal vector \(n\) and the direction of interest, and \(\varphi\) is the azimuthal angle. We assumed the system to be axisymmetric (i.e., there is no dependence on \(\varphi\)). The actual formulation of \(\varepsilon\) is unknown, but a simple model was used in this study, i.e., the \(\cos^{-1} \theta\) dependence. The motivation behind this assumption is as follows. High-energy GCR particles (\(\sim\)GeV) can penetrate an MCP. Therefore, the probability of a collision between a GCR particle and an atom in the MCP producing electron avalanches is proportional to
the pass length of the GCR particle through the MCP. The path length is proportional to \(\cos^{-1} \theta\). This simple formulation may only represent an ideal case, but in fact, a similar trend in the angular response of MCPs to the X-ray photons (5–20 keV) has been reported (e.g., Kondoh et al. 1988).

Using the \(\cos^{-1} \theta\) dependence, the MCP count is simplified to

\[
dC = j S R d\Omega, \tag{5}
\]

where \(R\) is the response to the particle coming from normal (\(\theta = 0\)), which is constant. Equation (5) clearly shows that the differential counts in the GCR-driven background counts are proportional to the solid angle of interest (\(d\Omega\)). Therefore, if a planet blocks the GCR particles, the reduction in the background counts would be proportional to the solid angle of the planet seen from the MCP. The blockage solid angle \(\Omega_p\) is pure-geometrically \(2\pi(1-\cos \alpha)\) with \(\alpha = \arcsin(R_p/r_{sc})\).

Here, \(R_p\) is the planetary radius and \(r_{sc}\) is the distance of the spacecraft from the planetary center. Taking the reduction by planetary blockage into account, the GCR contributing counts are

\[
C_{\text{GCR}}(r_{sc}) = B \cdot (4\pi - \Omega_p)/4\pi. \tag{6}
\]

Parameter \(B\) represents the total expected counts from GCRs with no planetary blockage. Because the spacecraft distance, \(r_{sc}\), changes over time, the contribution from the GCRs \(C_{\text{GCR}}\) also changes. The total background counts are thus simply:

\[
C_{\text{bg}}(t) = A + B(1 + \cos \alpha)/2, \tag{7}
\]

\[
\alpha = \arcsin(R_p/r_{sc}(t)). \tag{8}
\]

Here, \(A\) is the background count from the \(\beta\)-decay, which is assumed constant. The unit of the parameters \(A\) and \(B\) is the same as the one used for the raw background count values \(B_{\text{GEXRAW}}\) and \(B_{\text{VEXRAW}}\) in Equations (2) and 3).

By fitting the time series of the measured total background counts against the model (Equation (7)) along one orbit, we obtained the background counts contributed from the internal (A) and external (B) sources. The background counts and each contribution should always be a positive value. We thus constrained both the parameters to always be positive (i.e., \(A \geq 0\) and \(B \geq 0\)) for the fitting.

Figure 8 shows the typical background counts overlaid with the fitting results using the simple model (Equation (7)) \(R_M = 3396\ \text{km}\) and \(R_V = 6051\ \text{km}\). A clear dip in the background counts is visible, depending on the distance of the spacecraft to Mars or Venus. The lowest background counts can be seen in Figure 8(a) at a pericenter of \(\sim 250\ \text{km}\), when the apparent size of Mars was at a maximum. For Venus, precisely the same signature can be seen (Figure 8(b)). The depletions in the near pericenter indicate that a shadowing effect from the planets was also in operation. The best-fit parameter pair \((A, B)\) indicates the contributions of constant internal and time-varying external sources following Equation (7).

We were able to obtain one best parameter pair \((A, B)\) from each pericenter pass. Further statistical analyses will be possible from the 21,550 orbits of Mars Express between 2003 and 2021 January 18. Out of the 21,550 orbits, we only used the orbits during which continuous measurements were available around the pericenter (more than \(>50\) data point, equivalent to >160 minutes, within three hours of the time around the pericenter). There were 7371 orbits that satisfied this condition.

Figure 9(a) shows the statistical distribution of the best-fitted parameters of the internally \((A)\) and externally \((B)\) induced background counts. For the fitting, the constraints \((A \geq 0\) and \(B \geq 0\)) were applied in order to restrict the fitting, because neither component could negatively impact the background intensity. Surprisingly, many of the best-fit parameters were found at \(A = 0\) (Figure 9(a)). This implies that the time
variation represented by the external GCR should have a more significant influence than the simple geometric model.

Therefore, we performed a further examination by increasing the planetary radius (considered an obstacle to GCRs) by 100, 200, and 300 km, as shown in Figures 9(b)–(d), respectively. The cluster formed by the best \((A, B)\) pair was found at higher \(A\) and smaller \(B\) values, while the amount of data at \(A = 0\) was reduced significantly. While the quantitative assessment was not straightforward, these results suggest that the effective blocking radius must have been >100 km greater than the radius of Mars.

This is indeed a puzzling result, and the reason for the extraordinarily large effective blocking radius was inconclusive from the present analysis. While Mars has an atmosphere, any atmospheric effect that could reduce the GCR flux is expected to be small (Townsend et al. 2011; Radliff et al. 2017). On the other hand, our assumption of an isotropic GCR flux with a simplified cosine-dependence of the response function may possibly have created serious bias. In addition to the nonisotropic geometry of IMA structures, the body of a spacecraft is a great absorber of GCRs. Rotatable solar arrays that extended from a spacecraft body are sources of time-variable anisotropy. Slew operations near the pericenter can produce nonideal variations in the MCP background counts, because the relative geometries of the MCP, spacecraft, and Mars change. Considering all the above sources of nonisotropy, further investigations that assess the relative geometries of the IMA, the spacecraft body (especially the solar array), and the planetary body are essential to refining and explaining our results.

The temperature dependence is another open issue. In general, sensor temperatures become higher for lower altitudes, whereas they are more dependent on the time elapsing after the instrument has been switched on. Higher background counts might be expected with higher temperatures, because of higher electronic noise. If this is the case, the temperature-driven background count increase near the pericenter should be compensated for by the more significant decrease due to Mars, which requires a larger external contribution (term B). This requires a greater radius of Mars, implying that the temperature effect results in an opposite trend to explain the difference between the apparent GCR blocking radius versus the radius of Mars.

The same exercise was performed for Venus. Most of the best-fit \((A, B)\) pairs were already in the appropriate range without increasing the size of the effective blockage (Figure 10). Increasing the effective blocking radius did not produce any meaningful difference. We thus concluded that it was not possible to derive the effective blockage size for Venus.

### 6. Concluding Remarks

Here, we have reported the characteristics of the background counts measured by MCPs as part of the ion instruments, IMA, on board Mars Express and Venus Express. The background counts not only illustrated the previously reported sporadic SEP fluxes (e.g., Futaana et al. 2008; Ramstad et al. 2018) but also described the long-term trends in GCR intensity. The background data sets from Mars and Venus exhibited the well-established decadal modulation in terms of an anticorrelation to solar activity (Parker 1965; Guo et al. 2021; Knutsen et al. 2021). In particular, the 17 yr background data set from Mars Express showed an unusual signature associated with Solar Cycle 24 at Mars, which was consistent with that recorded on the Earth for Cycle 24.

We have also reported on the short-term modulations along a spacecraft trajectory caused by changes in the blocking effects of the planetary bodies. A simple model of GCR absorption was developed and applied to the data. Clear signatures of planetary blocking were found for both Mars and Venus. Further statistical analysis suggested that the effective blocking radius for GCR by Mars could be more than 100 km greater than the solid planetary body. Further investigations are needed.
to help us understand why an apparently greater absorption radius than the planetary radius was required.

Using a more sophisticated absorption model would definitely be one of the possible directions for future studies, where spacecraft shape should be considered because spacecraft also absorb GCR fluxes. For example, a GEANT-4 simulation (Allison et al. 2016) could be used to formulate the background count production function \( P(E, \Omega) \) more precisely. By understanding the geometric effect of the spacecraft’s body on the IMA background counts, monitoring might support an estimation of the residual liquid fuel inside the spacecraft. In addition, the relative geometry between the MCP, spacecraft (solar arrays), and Mars should be important. Furthermore, the transport of GCR particles in the tenuous Martian atmosphere and the production of secondaries should also be considered.

We obtained similar data sets from the electron and ENA sensors of Mars Express and Venus Express. These data sets can add further information, although the background count rates were lower due to their smaller MCP sizes. In addition, there is no obvious “background channel,” so careful separation from the real physical foreground counts is needed for the data analysis. On the other hand, the advantage is that these sensors have higher time resolutions (Posner et al. 2013). In addition, comparisons with the RAD measurement on the Curiosity rover (Hassler et al. 2012) and the MAVEN SEP instrument (Larson et al. 2015) are a natural development of this study.

Not many studies have investigated the interaction of MCPs with high-energy particles on planetary missions (Andre et al. 2019). Obtaining such information is critical to exploring the harsh Jupiter environment, such as for the JUpiter ICy moons Explorer (JUICE) mission. In addition to affecting robotic missions, high-energy particles are also a threat to human activities in the extraterrestrial environment. High-energy particles can also provide insights into astrobiology. The characterization of high-energy particles using MCP background counts from previous missions and instruments could potentially contribute to the study of the high-energy particle environment by offering increased spatial and temporal coverages. In fact, background counts contain extensive information entropy due to their randomness. Because of its poor compression rate, the background counts require high telemetry for downlink—a valuable resource in space and planetary exploration. In addition, the random background

Figure 9. Two-dimensional histograms showing the occurrence of the best-fitted pair of internally (term A) and externally (term B) originated counts measured at Mars. Panels show the respective assumed blockages with the (a) radius of Mars \((R_m = 3396\ km)\) and the radii (b) 3496 km \((R_m+100\ km)\), (c) 3596 km \((R_m+200\ km)\), and (d) 3696 km \((R_m+300\ km)\).
counts increase the load in the internal data processing. This resulted in the decision by the ASPERA-4 team to introduce the onboard background count subtraction scheme in 2010. However, we want to emphasize that the background counts from space instrumentation are not just costly junk. They contain valuable information that is not even the primary scientific objective of the respective sensors. Background counts in data archives from previous missions represent a buried treasure.

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The ASPERA data used in this study can be obtained from the FAIR-compliant NASA Planetary Data System (PDS; https://pds-geosciences.wustl.edu/missions/Mars_express/aspera.htm). Identical data sets are also available from the Planetary Science Archive (PSA; https://www.cosmos.esa.int/web/psa/Mars-express) and the SPICE kernel repository (https://www.cosmos.esa.int/web/spice/home) at ESA. We acknowledge the NMDB database (www.nmdb.eu), founded under the European Union’s FP7 program (contract No. 213007), for providing data. We also thank the University of Delaware Department of Physics and Astronomy, and the Bartol Research Institute, for providing high-quality data from the Thule neutron monitor for this study. The sunspot number data were retrieved from the World Data Center (SILSO), Royal Observatory of Belgium, Brussels.

This research made use of NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), iPython and Jupyter (Perez & Granger 2007), matplotlib (Hunter 2007), and pandas (McKinney 2011) software.

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**Figure 10.** Two-dimensional histogram of the calculated external/internal contributions at Venus, shown in the same format as in Figure 9 but with the only obstacles being spheres with (a) the radius of Venus ($R_V = 6051$ km) and (b) $R_V + 200$ km.
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