Energetic particles detected by the Electron Reflectometer instrument on the Mars Global Surveyor, 1999–2006

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[1] We report the observation of galactic cosmic rays and solar energetic particles by the Electron Reflectometer instrument aboard the Mars Global Surveyor (MGS) spacecraft from May of 1999 to the mission conclusion in November 2006. Originally designed to detect low-energy electrons, the Electron Reflectometer also measured particles with energies >30 MeV that penetrated the aluminum housing of the instrument and were detected directly by microchannel plates in the instrument interior. Using a combination of theoretical and experimental results, we show how the Electron Reflectometer microchannel plates recorded high energy galactic cosmic rays with \( \frac{C_24}{45\%} \) efficiency. Comparisons of this data to galactic cosmic ray proton fluxes obtained from the Advanced Composition Explorer yield agreement to within 10% and reveal the expected solar cycle modulation as well as shorter timescale variations. Solar energetic particles were detected by the same mechanism as galactic cosmic rays; however, their flux levels are far more uncertain due to shielding effects and the energy-dependent response of the microchannel plates. Using the solar energetic particle data, we have developed a catalog of energetic particle events at Mars associated with solar flares and coronal mass ejections, which includes the identification of interplanetary shocks. MGS observations of energetic particles at varying geometries between the Earth and Mars that include shocks produced by halo, limb, and backsided events provide a unique data set for use by the heliophysics modeling community.


1. Introduction

[2] Successful modeling of the propagation and evolution of solar energetic particles (SEPs) and interplanetary coronal mass ejections (ICMEs) is an ongoing effort in the heliospheric community for both scientific and practical purposes [Akasofu, 2001; Dryer et al., 2004; Hakamada and Akasofu, 1982; Schwadron et al., 2010]. The impact of these extreme examples of space weather on the terrestrial environment is well known, and include communications and power disruptions, damage or even the total loss of satellites, increased magnetospheric and auroral activity, changes in atmospheric processes including chemistry, and increased exposure to individuals at high altitudes or in low-earth orbit [Baker, 2000; Dyer et al., 2003]. While there is a long record of the impacts of these events, predictions for the timing of their arrival remains an active area of research, with a multitude of models in use that seek to adequately describe ICME evolution throughout the heliosphere. The timing and spatial properties of SEPs are also of interest, given their propensity to arrive suddenly after the onset of solar events. The impact of extreme space weather at Mars is an area of emerging and active research [Falkenberg et al., 2011a; Falkenberg et al., 2011b; McKenna-Lawlor et al., 2008; McKenna-Lawlor et al., 2005]. Relatively unmagnetized bodies such as Mars do not possess a coherent magnetosphere and thus their ionospheres are relatively unshielded from space weather events, which likely lead to interactions deeper in the atmosphere than for magnetized bodies [Crider et al., 2005;
Previous work examining the impact of solar events at Mars includes characterization of shocks associated with large flares in March of 1989 using data from Phobos-2 [Aran et al., 2007; McKenna-Lawlor et al., 2005]. More recently, Zeitlin et al. [2010] summarized solar particle events and galactic cosmic rays (GCRs) recorded by several instruments on Mars Odyssey between 2002 and 2006. Efforts are also underway to understand the propagation of ICMEs to the outer heliosphere using a variety of observations from multiple spacecraft including Ulysses, WIND, Voyager, and Pioneer [Gazis et al., 2006; Liu et al., 2005; Richardson et al., 2006; Steiger and Richardson, 2006; Wang et al., 2005].

While progress in multipoint measurements of solar activity is being made, observations beyond 1 AU remain limited. Our analysis of data from the Electron Reflectometer (ER) instrument onboard the Mars Global Surveyor (MGS) spacecraft provides a unique opportunity to examine the propagation of SEPs and ICMEs beyond 1 AU and over a variety of Sun-Earth-Mars phase angles. The data set from MGS that we present here contains a multitude of time-intensity variations, which generally follow the expected profiles depending on the geometry between the observer and the source given prevailing conditions in the interplanetary magnetic field (IMF). The events we characterize include typical east, west, and halo CMEs, exceptionally wide and intense events such as Bastille Day in 2000 and the Halloween events in 2003, as well as backsided events witnessed from the perspective of Earth. The varying geometries between the Earth and Mars that occurred during the MGS mission have enabled multipoint measurements of ICMEs during halo events when these planets were in opposition, as well as the measurement of arrival times of limb events as seen from Earth when Mars was leading or trailing the Earth. Backsided events were also observed in which our observations from the ER provide estimates of shock arrival times that were previously unavailable. We also characterize the longitudinal extent of some events, with a few cases showing clear effects of shock curvature in addition to propagation time.

In the next sections we first describe the ER instrument and develop a model that describes its response to high energy, minimum ionizing particles using a combination of previous experimental work and theory on the effects of energetic particles on microchannel plates (MCPs). As a test case that demonstrates the validity of our theory for the MCP response, we show that the resulting background in the ER instrument outside of disturbed solar conditions is consistent with known GCR fluxes throughout our period of observation. The theory describing the MCP response applies to energies down to a few MeV, thus enabling an estimate of the response to SEPs as well. While the flux of GCRs is relatively well-constrained, flux levels for SEPs are complicated by the fact they are lower in energy and hence more susceptible to the effects of shielding, and may also exhibit spatial non-uniformities that interact with the field-of-view (FOV) for penetrating particles. Although some information is gained in terms of event intensities, uncertainties in the flux levels for SEPs indicate that the main contribution of the observations made by the ER is in the timing and spatial properties for both SEPs and interplanetary (IP) shocks related to ICMEs. Based on our detection mechanism outlined above, we then summarize the SEP events and candidate ICMEs as seen by MGS throughout a nearly 7-year period starting in mid-1999, and describe a data set for use by the community in SEP and ICME propagation modeling.

The MGS Mission and ER Instrument

The MGS spacecraft arrived at Mars in September of 1997 and was inserted into a circular mapping orbit in March of 1999, with a nominal 400 km altitude fixed in a 2 A.M.-2 P.M. local time plane. Contact was lost with MGS on 2 November 2006, and the mission concluded shortly thereafter. Onboard MGS, the MAG/ER instrument consisted of a 3-axis fluxgate magnetometer (MAG) combined with the ER, a top-hat style electrostatic plasma analyzer [Acuña et al., 1999, 2001; Carlson and McFadden, 1998]. The MAG instrument was designed to study in situ magnetic fields arising from Mars-solar wind interactions and any intrinsic or crustal magnetization, while the ER was designed to study the Martian ionosphere, the interaction of Mars with the solar wind, and to perform remote sensing of magnetic fields via the electron reflection technique [Mitchell et al., 2001]. Nominally, the ER instrument was intended to measure the energy and angular distribution of low-energy electrons between ~10 eV and ~20 keV. In a basic electrostatic analyzer design, the electrons enter the detector via a narrow entrance aperture and are subsequently guided onto MCP detectors via a system of electrostatic deflection (Figure 1a). As the potential is swept between the two concentric spherical shells, only electrons of a specific energy range avoid collisional absorption into the entrance aperture walls, which are then focused on to MCP assemblies arranged in an annular ring to cover the analyzer exit plane. The MCPs amplify the incoming electrons via a cascading avalanche process, leading to the impact of a much larger number (~10^6) of electrons on an anode beneath the MCP. By recording the angular position of the charge pulse impact on the anode plane, the direction of arrival of the electron can be determined. The MCP assemblies in the ER were constructed using two individual MCPs stacked on top of one another in a chevron configuration [Carlson and McFadden, 1998; Fraser, 1983; Wiza, 1979]. The anode used in the ER was a circular pulse-position anode (PPA), a resistive element design that relied on the timing of arrival of two charge pulses at the anode ends to localize the approximate location of the arriving particle along the anode ring. Under typical operating conditions, the energy resolution provided by the ER analyzer section was ΔE/E ~25%, and the PPA yielded position to within ~1° of accuracy.
Direct qualitative evidence that the ER detected particles with energies significantly above the limit of the highest energy channel consists of isolated periods of enhanced count rates whose temporal profile suggests that they were associated with known solar events. Many of these examples possessed clear shock features consistent with plausible IP shock propagation times. Under normal circumstances the ER recorded both solar wind and ionospheric electrons over a range of \( \text{\~10} \text{ eV} \) to \( 20 \text{ keV} \), including their angular dependence within the FOV. The uppermost energy channel covered a range of \( 16\text{–}20 \text{ keV} \), and was generally quiet with a typical rate of \( \approx5\text{–}15 \text{ counts/s} \), except during rare periods when energetic electrons were encountered in the Martian plasma environment. During isolated time intervals, the ER count rates increased dramatically across all energy channels and angles, typically above \( 10^5 \text{ counts/s} \) and in some cases as high as \( 10^6 \text{ counts/s} \).

[5] Figure 2 displays data from one such event in January of 2002, showing the uppermost energy channel of the ER during otherwise quiet ionospheric conditions. Looking at data from Earth, the sudden rise in count rate is coincident with a C9 class flare as seen by the Geostationary Operational Environmental Satellites (GOES) and the emergence of an east-limb CME [Cane et al., 2006]. Roughly 2 days later, a sharp spike in the count rate was observed. This signature is consistent with a gradual proton event (GPE), in which SEPs stream to Mars along magnetic field lines connected to the source region, followed by the ICME.

Figure 1. (a) Electron Reflectometer (ER) instrument design and operating principle and (b) schematic of ER on the main payload deck of the Mars Global Surveyor (MGS) spacecraft, showing top-hat location, MCP orientation, and fields of view.

Figure 2. Example of enhanced count rates in the highest energy channel of the ER during January 2002. The count rate appeared relatively independent of energy in the upper three energy channels. The intensity-time profile and duration, together with onset just after a known flare/coronal mass ejection (CME), is consistent with a gradual solar energetic particle (SEP) event.
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Storm Particles (ESPs)
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ICME shock front, culminating in the passage of the shock
results from the continual acceleration of particles at the
average the aluminum housing of the ER instrument. These
caused by energetic particles, mostly protons, which pen-
eterated the aluminum housing of the ER instrument. These
penetrating particles thus bypassed the energy selection
method employed by the ER, and hence appeared uniform
in count rate across the energy channels. These events
were typically detected at the uppermost energy channels,
while counts due to ionospheric and photo-electrons
tended to dominate the lower energy channels. The sus-
tained flux of particles in the higher energy channels results
from the continual acceleration of particles at the
ICME shock front, culminating in the passage of the shock
itself which brings a rapid increase in flux – the Energetic
Storm Particles (ESPs) – at 07:10 on 11 January 2002 in
this event.

The distribution of material around the MCPs within
the ER was somewhat complex, such that an exact
description of the attenuation of energetic particles due to
shielding is for the most part impractical. However, a sim-
plified model of the shielding distribution can be developed
that is sufficiently accurate for our purposes here, depend-
ing on the arrival direction and the energy of incoming high
energy particles. The ER instrument was mounted on the
MGS instrument deck, which was generally facing in the
nadir direction (toward Mars) throughout the mapping
mission (Figure 1b). The ER detector head, containing the
aperture, electrostatic analyzer section and MCP detectors
protruded beyond the deck line in order to facilitate a clear
FOV in the aperture plane for low energy (<20 keV) elec-
trons. We define the y axis to face out away from the
detector head as shown. In the hemisphere defined by the
y-axis looking along y, the shielding surrounding the MCP
detectors ranged between 3.6 and 4.8 mm, the majority of
which was comprised of aluminum with some smaller
proportion of plastics. In the opposite direction (−y) the rear
of the ER assembly consisted of an electronics box, with
aluminum sides ranging between 0.75 to 1.75 mm in thick-
ness, in addition to fiberglass circuit boards and compo-
ents within the box. However, the FOV in the −y direction
was also obscured by other instruments and their elec-
tronics boxes on the MGS payload deck, thus there was
substantial shielding in this look direction. Part of the
rearward-facing hemisphere in the −y direction was also
obscured by the payload deck, a section of MGS containing
avionics, and main fuel tanks, all enclosed in a composite
structure. In the −z (nadir) direction, the FOV was obscured
in a 63° cone by Mars. Thus for energetic particles, the side
of the detector with the lowest energy threshold for pene-
tration into the interior was from the +y direction. We
conducted simulations utilizing Stopping Range of Ions in
Matter (SRIM) to determine that on average, protons of
greater than ~30 MeV energies could penetrate the amount
of aluminum present around the MCPs when incoming
from the +y hemisphere, with a variation of several MeV
due to the distribution of shielding, with the caveat that
a portion of the FOV in this direction is obscured by
Mars. Given that the SEP spectral knee ranges between
~10 MeV to ~1 GeV [Reames et al., 2001], with this
threshold the ER should have been sensitive to a large
number of SEP events with sufficient energy to penetrate
the aluminum housing and directly impact the MCPs
within the instrument.

3. Data Set Description

[S] The complete record of energetic penetrating particles
recorded in the ER instrument is shown in Figure 3. The
black trace represents the raw data from the highest
energy channel, summed over all pitch angles, in corrected
counts/s. For the data shown, this channel contains
enhanced counts due to individual solar energetic particle
events as well as ~20 keV electrons that entered the
instrument aperture and were energy-selected by the
voltage sweep as intended for nominal operation. The red
regions indicate areas of SEPs, selected manually, using a
database of known solar events, supporting data from
other spacecraft, visual inspection of the temporal profile,
and apparent pitch angle characteristics and energy spec-
tra. High (10^3/s) count rates recorded during SEP events
were corrected for dead-time. Overall, between May of
1999 and November of 2006, the ER detected 85 discrete
events consisting of enhanced counts in the highest three
ergy channels. The majority of these are consistent with
the presence of energetic particles penetrating the detector.
Outside of the SEP enhancements and ~20 keV electrons,
the background count rate is shown as a smooth line in
Figure 3, which ranged from a minimum between mid-
2000 to 2004, and approached maximums in early 1999 and
late 2006. The background count rate reached a minimum
of ~6 counts/s in 2001 and obtained a maximum level of

Figure 3. Complete energetic particle data set/
summary from the ER. Black represents raw data in the
highest energy channel, red indicates selected events
consistent with particles that penetrate the instrument
housing, and the light blue line indicates smoothed,
averaged background outside of known solar activity.
counts/s at the conclusion of the MGS mission in November 2006.

4. Detector Response to Penetrating Particles

The modulation in the background count rate in Figure 3 presents a clue to its origin, in that this dependency is consistent with the expected modulation of the GCR flux by the solar cycle. GCRs provides an attractive method to understand the ER detector response to penetrating particles in general, since the energy distribution peaks near ~1 GeV, which will penetrate through most of the material surrounding the ER on MGS. Thus of the various sources of energetic particles that may be present, the detector response to GCRs is the most likely to be relatively independent of the shielding distribution around the MCPs, and hence representative of the raw MCP response to high energy particles.

MCPs are typically optimized for the detection of lower energy ions and electrons in the keV regime, in which incoming particles stimulate the emission of secondary electrons at the channel walls, initiating a cascade effect resulting in amplifications of \(10^6 \sim 10^7\). MCP efficiencies in this energy regime for incident ions have been studied experimentally and theoretically for decades, in most cases for ions energies of less than a few hundred keV [Fraser, 2002]. In this regime secondary electron production is assumed to result from close nuclear collisions between the incident charged particles and atoms in the target material (in this case MCP glass), producing energetic electrons (\(\delta\)-rays). These \(\delta\)-rays then proceed to ionize additional atoms within the MCP glass, producing lower energy secondary electrons, which may then migrate to the surface via a diffusion process [Sternglass, 1957]. There is however ample evidence that MCPs can respond to higher energy particles with reasonable overall efficiencies depending on the circumstances. Oba et al. [1981] performed an experimental study of the efficiency of stacks of MCPs to \(3\) GeV/c pions and \(7\) GeV/c protons, obtaining overall detection efficiencies ranging from 50 to 90% depending on the number of MCPs used in the stack and angle of incidence. More recently, Mosher et al. [2001] describe the use of MCPs to detect ions with MeV energies and masses between \(A \sim 3 - 200\) in nuclear recoil experiments, with absolute efficiencies approaching 80% for alpha particles. Work by Sigmund et al. [1989, 1988] demonstrated \(\sim 65\%\) overall efficiencies for their MCP configuration to GCR-produced secondary muons at sea level, using a coincidence counting technique, and also isolated the pulse-height distribution of these events.

The detection efficiency for energetic, minimum ionizing particles by MCPs can be substantial due to the fact that these particles can penetrate through many MCP channel walls. Thus while the probability of electron emission per collision with a wall of an individual MCP channel may be small, since many such channel walls are penetrated during a given particle traversal, the overall aggregate probability of one or more electrons being generated can be significant (Figure 4a). The results of Oba et al. [1981] are consistent with this interpretation, who observed an angular dependence for MCP efficiencies that was proportional to the number of channel walls penetrated by incident \(3\)–\(7\) GeV/c particles (Figure 4b). The lowest efficiency occurs as one approaches normal incidence (\(\alpha \sim 90^\circ\)) since particles cross the fewest number of channels at that angle of entry. Incoming particles with lower angles of incidence
begin to cross a larger number of channels laterally, and hence have a higher overall detection efficiency. Based on the results of Oba et al. [1981], the probability of electron emission at each MCP channel wall for \( \sim 7 \) GeV/c protons at a \( \sim 45^\circ \) angle of entry was estimated to be \( \sim 0.6\% \). For a typical MCP length-to-diameter ratio \( (L/d) \) of \( \sim 80 \), a particle entering at \( \alpha \sim 45^\circ \) will cross about 80 channel walls. Assuming Poisson statistics (see Appendix A), this yields a 38% probability that a minimum ionizing particle will liberate one or more electrons from the channel walls along its trajectory through the MCP stack. These electrons are consistent with \( \delta \)-rays, i.e., energetic electrons produced by ionization of the target material from the incoming charged particle, and are able to escape directly into the channel and then stimulate a cascade. For a typical MCP wall thickness of \( \sim 3 \) um, a \( \delta \)-ray produced in the middle of the channel wall would need a relatively low energy of \( \sim 19 \) keV in order to escape.

5. ER Detection Efficiency for Energetic Protons

Under the assumption that the slowly varying background levels in the highest energy ER channel in Figure 3 resulted at least in part from the solar cycle modulation of GCRs, we compared this data to simultaneous measurements of GCR protons obtained by the Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE) mission [Mewaldt et al., 2010]. The background counts in the ER were manually scanned to avoid known solar events, and then the remaining intervals selected based on the uniformity of counts across the top three energy channels. This data was then averaged over Bartels rotations, producing a single value of the estimated background per rotation. These results were then compared with measurements of GCR protons \( \sim 120 \) MeV by the CRIS instrument order to derive an effective sensitivity factor for the ER MCPs in this regime.

To effectively perform this comparison, several assumptions need to be made in terms of the equivalent MCP FOV under these conditions as well as the efficiency of MCPs with respect to heavier ions in addition to protons. To address the first issue, we assume that the shielding provided by the spacecraft to particles of GCR energies is negligible; previous work comparing the free space GCR response compared to the presence of spacecraft shielding for the MARIE instrument indicates that this is at most a 10% effect on Mars Odyssey [Astell et al., 2004]. The MCP is then modeled as a single planar detector of area \( A \) where shielding results solely from the fraction of the FOV that is obscured by Mars. The second issue is the response of the MCPs to fully ionized helium and heavier ions, which together can account for roughly 9–13% of the proton flux over solar cycle 23 [Shikaze et al., 2007]. The equivalent counts resulting from the heavy ion component of the GCR spectrum were accounted for in the ER background when compared to the CRIS proton data. Additional assumptions included that the variation in GCR flux between Earth and Mars is minimal, amounting to a few percent or less [Heber et al., 1995; McDonald et al., 1997]. Due to the high energy peak in the GCR spectrum (\( \sim 700 \) MeV–1 GeV), the difference between the GCR proton flux measured by the ER and CRIS due to the difference in particle energy threshold for each instrument (\( \sim 30 \) MeV versus \( 120 \) MeV) is also small, of order a few percent or less. A direct statistical comparison between the ER and CRIS data was then conducted, assuming the CRIS data as a standard reference. The ER background counts and CRIS proton data were binned and sorted from least to greatest values, and a linear least squares fit conducted. The results, shown in Figure 5, were statistically robust and imply an effective geometric factor \( G_{\text{ER}} \) for the ER with respect to GCR protons of 33.11 cm\(^2\)-s-sr. An ideal detector of area \( A \) would have a geometric factor of \( G \sim 2\pi A \), which is \( \sim 95.5 \) cm\(^2\)-s-sr in the case of the ER MCPs. Obscuration of the MCP FOV by Mars reduces this value by \( \sim 23\% \), or to \( \sim 73.5 \) cm\(^2\)-s-sr. Thus \( G_{\text{ER}} \) for GCR protons is \( \sim 45\% \) of the value expected for an ideal detector with 100% detection efficiency with an FOV obscured by Mars. Given this geometric factor for the ER with respect to energetic protons, the implied efficiency for the production of an electron at each MCP channel wall at an angle of incidence of \( \alpha \sim 45^\circ \) ranges from 0.7 to 1.4%. The uncertainty in this estimate is dominated by uncertainties in the total volume of the ER MCPs that can produce a detectable pulse when a penetrating particle initiates a \( \delta \)-ray, the details of which are discussed in Appendix A. The lower limit for the per-channel probability we obtain for the MCP ER is roughly consistent with the value estimated by Oba et al. [1981], and implies that only the upper (first) MCP of the ER was involved in the detection process.

The response of the ER MCPs to SEPs is in most cases assumed to result from the same mechanism as outlined for GCR ions. Although SEPs are lower in energy, their energy transfer during a traversal through the MCP glass is small compared to the incoming particle energy,
and as in the case of GCRs the thin target presented by the channel walls allows for the direct escape of $\delta$-rays. However, the interpretation of the overall response of the ER to SEPs is complicated by multiple competing effects when compared to the GCR response. As the proton energy decreases, the importance of shielding effects increases. For incident particles of $\sim$100 MeV energy, the distribution of material in the MGS spacecraft around the ER instrument likely played a significant role in reducing the incident flux on the MCPs. In the 10–100 MeV regime, the raw efficiency of the MCP itself becomes energy dependent, as discussed in Appendix A. Hence variations in spectral hardness have a significant impact on the overall ER efficiency for the detection of SEPs. In addition, SEP events may have anisotropic pitch angle distributions with respect to the magnetic field, unlike the nearly isotropic GCR flux. Since the response of MCPs to energetic particles is directional, the measured flux levels will depend on the orientation of the detector with respect to the magnetic field. Without coincident measurements of the SEP energy spectrum and pitch angle distribution, as well as a detailed knowledge of the complete distribution of material around the ER, determination of the absolute flux level of SEPs is difficult. While electrons comprise less than 1% of the GCR flux, it is also worthy to note that energetic electrons above a few MeV may also have penetrated the ER housing, and would have produced counts directly in the MCPs with similar efficiencies as in the case of ions outlined above [Bateman, 1977]. Gradual SEP events are generally electron poor, while the impulsive events may contain a significant electron population, thus the importance of this effect will vary from event to event [Reames, 1999b]. SEP flux estimates from ER data may be possible on a case-by-case basis depending on the availability of other measurements, particularly for isotropic distributions and when the SEP energy spectrum is known from other sources. The determination of the absolute flux for individual SEP events in the ER data set is beyond the scope of this paper and will be left for future work. The primary objective in our present analysis is to identify the physical mechanism responsible for the detection of SEPs by the ER, which utilizes the response of MCPs to GCR protons to show that this occurs due to the interaction of energetic particles with individual MCP channel walls.

[16] Thus to summarize our results, the response of the MGS ER to energetic particles may be described as follows:

[17] 1. Over at least half of the FOV, the ER instrument housing allows the penetration of protons of $\sim$30 MeV energy which will then directly impact the MCP plane. The energy threshold for penetrating protons is at this level or higher in other look directions depending upon the amount of shielding provided by the MGS spacecraft.

[18] 2. GCR protons represent an excellent test case in which to quantitatively constrain the efficiency of the ER instrument for the detection of energetic particles. Assuming that shielding is negligible and that the sensitive region is provided by the MCP active area, the detection efficiency is consistent with the presence of a small but measurable probability of electrons produced through $\delta$-ray emission at each MCP channel wall. The overall MCP efficiencies and detection probabilities per channel wall we derive using CRIS proton data as a reference are comparable with previous laboratory measurements of MCP efficiencies for energetic particle detection.

[19] 3. The detection efficiency for heavier ions in the ER instrument was greater than 80%. This is due to the dependence of $\delta$-ray emission probability on the square of the particle charge $z$, and correspondingly higher linear energy transfer (LET) for these particles.

[20] 4. Detection of lower energy SEPs by the ER MCPs occurs through the same mechanism as we outline for GCRs above. However, the determination of absolute flux levels for incident SEPs is complicated by the increased importance of spacecraft shielding at these energies, the energy dependence of the MCP response in this regime, the possibility that the particles may have anisotropic pitch angle distributions, and the presence of low-energy (keV) or penetrating (MeV) electrons.

6. Solar Energetic Particles

[21] The ER detected numerous isolated events of enhanced count rates meeting the criteria for the presence of penetrating particles above the levels produced by the continual GCR flux. To isolate these events, a signal-to-noise (SNR) ratio of $\sim$3 was used as a threshold, requiring that the enhanced counts be above the ER background by at least this amount. While the background varies over the data set depending on cosmic ray and noise backgrounds, in general any event with a peak less than 30 counts/s or less was ignored. Extremely short duration events, consisting of less than three data points (or $\sim$15 min) were also ignored. Uniformity in counts in the top three energy channels was also used as an indicator of the presence of penetrating particles. Many events with count rates $>100$ counts/s produced counts in the top three energy channels with a high degree of uniformity, typically within 20% of one another. Outside the events, the ratios of counts in the uppermost energy channels usually exceeded a factor of 2. Finally, known periods of obvious ionospheric activity and other contaminating sources such as stray light were discarded.

[22] The resulting data set was then processed to select for events with a significant flux for particles $>30$ MeV of $\sim$1 particle/cm$^2$-s-sr. As described earlier an exact geometric factor for each SEP event is unknown, but as an approximation we assumed an average geometric factor of $\sim\pi A$ for the detection of most SEP events, equivalent to a count rate of 45–50 counts/s in the uppermost energy channels of the ER. Of these, a subset was identified whose onset was temporally correlated with the detection of a significant CME by the Large Angle and Spectrometric Coronagraph Experiment (LASCO) on the Solar and Heliospheric Observatory (SOHO). Associated flare activity was acquired through the LASCO CME catalog and/or GOES X-ray observations. The result of this selection process was 41 events linked with a specific CME, or group
Table 1. Summary of SEPs Related to Solar Events Detected by the MGS/ER, May 2000–Aug 2005

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<thead>
<tr>
<th>Number</th>
<th>Date (Mars)</th>
<th>ESP Arrival</th>
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<th>Date (Earth)</th>
<th>ESP Arrival</th>
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<th>LASCO Detection</th>
<th>Shock Arrival</th>
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<td>–</td>
<td>153</td>
<td>Backsided CME</td>
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<td>13:05</td>
<td>–</td>
<td>60</td>
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<td>X5.7</td>
<td>7/14/00</td>
<td>10:24</td>
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<td>N22W07</td>
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<td>174</td>
<td>Bastille Day</td>
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<td>Cane et al.</td>
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<td>3</td>
<td>7/27/00</td>
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<td>Gradual onset of SEPs followed by clear shock signature in ESPs.</td>
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<td>Fast CME on 4/2, 22:06, or several partial halo events on 4/2.</td>
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<td>7/14/05</td>
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<td>216</td>
<td>M5</td>
<td>7/13/05</td>
<td>14:01</td>
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<td>Backsided event on 8/8/04 at 08:54 is one possible source. Several SIRs may be present.</td>
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\(a\) All times are in UT.

\(b\) Sun-Mars time is given in decimal days.

References:
- Jian et al. [2006b] event 24, 25
- Jian et al. [2006b] event 28
- Jian et al. [2006a] event 18
- Cane et al. [2006] event 86
- Cane et al. [2006] event 90
- Cane et al. [2006] event 91

CMEs on 9/3/04 at 00:54 and 10:30 and on 9/4/04 at 06:54. Occurs near an SIR. Possibly event 18 in Jian et al. Related to several halo CMEs on 1/15/05. No LASCO coverage during this time. GOES x-ray data indicates M4 flare on 6/16/05, 20:01. Halo CME on 7/21/05 at 03:54. SIR identified by WIND. Consistent with energetic penetrating particles but origin unknown. Consistent with a shock from one of two Halo events on 8/22/05 at 01:30 and 17:30. Earth detects two closely spaced shocks that may have merged at Mars.
of CMEs, and are summarized in Table 1. Of these, roughly half (21 events) were associated with a specific CME with reasonable certainty; these events typically showed prompt arrival of SEPs from a known flare/CME and had good correlation with other energetic particle data detected at Earth. The remaining events were generally associated with a group of CMEs. The presence of stream or corotational interaction regions (SIRs/CIRs) were also noted, although detection of these by the ER was unlikely given the ≈30 MeV energy threshold for penetrating particle measurements.

[23] Parameters listed in Table 1 include the event number for this subset in column 1, which ranges from 1 to 41. Column 2 shows the SEP arrival time at Mars, chosen using the SNR = 3 criteria in particle count rate described earlier. Estimated shocks at Mars are shown in column 3 of Table 1, identified in the data set by the presence of ESPs, the rapid increase in energetic particle intensity expected for faster ICMEs [Kallenrode, 1995; Lario et al., 2005; Mäkelä et al., 2011], hence this column is denoted “ESP Arrival.” The ER peak count rate is listed in column 4, which is provided to give some indication of the intensity of each event. As discussed earlier, the interpretation of these rates in terms of absolute flux is subject to limitations. In cases where clear shock and CME identification has occurred, the transit time from the Sun to Mars is listed in column 5 in decimal days. Columns 6–11 summarize known solar event properties including flare intensity, time, and location, applicable active region (AR), detection time of a CME by LASCO, and shock arrival times at Earth. Flare data was obtained using the Virtual Solar Observatory (http://vso.nso.edu/cgi/catalogui) and also relevant published work for specific events of interest (such as the 2003 Halloween storms). Shock arrivals at Earth, including screening for the possible presence of SIRs, are listed using data compiled by Jian et al. [2006a, 2006b], supplemented by the ACE Lists of Disturbances and Transients (http://www-ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html). Column 12 shows the relative solar longitude angle (ϕ) between Earth and Mars, obtained using the online Mars ephemeris generator maintained by the NASA Planetary Data System (http://pds-rings.seti.org/tools/ephem2_mar.html). In the convention adopted here, ϕ is defined as positive in the counterclockwise direction, looking down on the ecliptic plane from the direction of solar north. Positive ϕ indicates that Mars is leading the Earth in this plane, and negative ϕ is for cases when Mars trails the Earth. Column 13 contains notes specific to each event, such as lists of potential candidate CMEs in the cases where an event cannot be attributed to a single CME, and other observations of specific interest to each case. Column 14 contains references to other relevant work in shock identification, and to specific events as appropriate. All times shown in Table 1 are in Universal Time (UT).

[24] Detection of an ICME in our data set is limited to cases with clear SEP and ESP profiles. The main indicator used to identify shock arrival at Mars is through the presence of ESPs in the penetrating particle signature. The presence of ESPs is far from comprehensive in terms of ICME identification, where other in situ phenomena such as above-ambient magnetic fields, magnetic clouds, bi-directional electron strahls (BDEs) and low proton or electron temperatures have proven more diagnostic, among other observables [Cane and Richardson, 2003; Gopalswamy et al., 2001; Jian et al., 2006a; Zurbuchen and Richardson, 2006]. Use of ESPs as the primary shock identification tool will likely isolate only the faster shocks (>1000 km/s) and may miss ~50% of CME-related shocks [Mäkelä et al., 2011]. To aid in the identification of shocks and ICME-related discontinuities, we also used the magnetometer data from MGS as a proxy for solar wind pressure to provide corroborating evidence of an ICME passage. The subsolar magnetic field strength is estimated by fitting the magnetic fields measured by MGS in the mapping phase to a cos^2θ function, where θ is the angle between the upstream flow and the obstacle normal. Measurements obtained in the magnetic pileup boundary (MPB) are dominated by magnetic pressure, which is assumed to scale with incident solar wind dynamic pressure. The resulting fit thus yields a proxy for the solar wind pressure at a timescale of the MGS orbital period, or in roughly ~2 h increments [Brain et al., 2005; Crider et al., 2003]. As an example of the applicability of this technique to ICMEs, Crider et al. [2005] showed that large increases in the solar wind dynamic pressure were present at Mars during shocks associated with the 2003 Halloween events. For all but one of the candidate shocks identified in our data set using ESPs, there was an accompanying significant increase in the magnetic field pressure proxy.

7. SEP Temporal and Spatial Properties

[25] Throughout the MGS mission, the ER detected SEP events over a wide range of Earth–Mars geometries, thus adding a second observation point with which to constrain SEP spatial properties. In general, the duration and time-intensity profiles of most of the events in Table 1 are consistent with GPEs, resulting from the small fraction (~1%) of CMEs with fast shock speeds and hence capable of the sustained acceleration of particles. These events show many of the typical temporal-spatial variations depending on the geometry of the source and observation point. These include the expected time-intensity profiles for halo events and for sources both to the east and west of the observer, as well as exceptionally wide events, and back-sided events that would previously have gone uncharacterized in terms of SEP and shock arrival times. There was also at least one example of an event showing the clear effects of shock curvature. We describe in detail a few examples of these different classes of events below.

[26] When measured from a single location, the intensity-time profiles of SEP events will depend in large part on the location of the event with respect to the central meridian from the perspective of the observer [Reames, 1999a; Richardson et al., 1991]. Particles accelerated from regions to the west from the perspective of the observer will arrive promptly at time scales comparable to the propagation time, as these particles stream along the
magnetic field lines oriented along the Parker spiral that intercept the observation point, followed by a maximum in particle flux as the shock itself passes. The onset of SEPs is usually more gradual from events to the east, since these regions are not well magnetically connected to the observer, but will rise in intensity as the shock expands and shock-accelerated particles begin to arrive. Events near the central meridian may produce a wide variety of time-intensity profiles depending on the width of the CME, and often result in a plateau in the SEP time-intensity profile with the exception of a shock-enhancement.

Figures 6–8 summarize examples of halo, east, and west events as seen from Earth, with supporting data from the ER. The Halloween storm of 2003 provided one of the most straightforward examples of a halo CME in which both Earth and Mars were magnetically connected to the same particle acceleration region. During this time Earth and Mars were in opposition, with Mars slightly trailing Earth such that it was very likely on the same Parker spiral field line. These are listed as events 28–30 in Table 1 and are summarized in Figure 6. An X1.2 flare/CME occurred on 26 October at 17:54 UT, resulting in the prompt arrival of SEPs at both planets. At 09:51 UT on 28 October, an intense X17 flare erupted, followed by a fast halo CME at 11:30 UT. Prompt SEP arrivals are evident at both Earth and Mars in Figures 6b and 6e, followed by the shock arrival separated by less than 23 h between each location. The next most obvious feature is the prompt arrival of SEPs at both Earth and Mars on 2 November, resulting from an X8.3 flare at 17:03 UT followed by detection of a CME at 17:35 UT, where again Earth and Mars were magnetically connected to the source region. It should be noted that between these events
a fast (>2000 km/s) halo CME on 29 October at 20:54 UT was recorded from an active region near the central meridian, hence flare or shock-accelerated particles were not well-connected to Earth or Mars. There may be some evidence of a subsequent shock at Mars, marked by both a magnetic enhancement and a slight increase in the penetrating particle flux on 31 October at ~12:00 UT; however, this determination is far from certain.

Figure 7 shows data from the example of a CME in January 2002 presented in Figure 2, listed as event 20 in Table 1, when a CME was detected by LASCO on 8 January 2002, 17:54 UT, with an eastern component as it expanded. While there was a C7.2 flare from an active region at S18° W42° at this time, closer inspection indicates that a more likely source was a C9 flare in the northern hemisphere and behind the east limb (NE100°). In the data shown, no initial SEPs were detected at Earth, but a shock was witnessed on 10 January 2002 at 15:50 UT. The ER detected both the initial SEPs and a subsequent shock on 11 January 2002 at 07:10 UT. Mars was trailing the Earth by ~77° during this time, i.e., was in the direction of the east limb as seen from Earth, and thus from the perspective of Mars the source of this event was close to the central meridian. In this case there was a gradual onset of the event at Earth during and after the shock passage, as is typical for east limb events [Cane et al., 2006]. The ER recorded both the initial SEPs as well as a shock, consistent with a halo event from the perspective of Mars. The prompt SEPs were most likely accelerated from the expanding ICME shock front as it moved in the easterly direction and achieved magnetic connection with Mars. Eventually the ICME shock front became sufficiently wide to be detected at both Earth and Mars.

As with east limb events, west limb cases also demonstrated the expected profiles when compared between
the Earth and Mars. Figure 8 shows the data from event 4 in Table 1, in which Mars was leading the Earth (Earth-Sun-Mars angle of \( \sim 123^\circ \)) and was thus in the direction of the west limb as seen from Earth. A CME on 16 October 2000 at 7:27 UT occurred on the west limb. In this case the Earth was magnetically connected to the source region where initial particle acceleration was occurring, and witnessed the prompt arrival of SEPs. Mars was evidently too far west to be magnetically connected to the source, thus no initial SEPs were detected. Meanwhile, the shock was traveling from the direction of the west limb, missed the Earth but clearly impacted Mars on 20 October 2000 at 00:07 UT.

\[30\] The ER also recorded the Bastille Day event in 2000 (Figure 9 and event 2 in Table 1), when Earth and Mars were in conjunction (separated by almost 180°). Table 1 lists the X5.7 flare during the Bastille Day epoch that preceded the arrival of a rapid rise in SEPs at Earth, along with the shock associated with the fastest CME recorded during that period. The ER recorded a modest but measurable increase in SEPs roughly 3 h after the arrival of SEPs at Earth. Given the location of AR9077 and the relative geometry between Earth and Mars, magnetic connection to the same source region is clearly unlikely; the SEPs at Mars must have resulted from acceleration at an extremely wide shock front in the resulting ICME. While there was no clear shock feature in the ER data, there was enhanced magnetic pressure proxy activity throughout, including a spike near 16 July, 02:00 UT.

\[31\] Figure 10 shows an example of a backsided CME that occurred when Mars led Earth by \( \sim 138^\circ \) (event 24 in
The time-intensity profile suggests that magnetic connection from Mars to the source region or the early expanding shock front was likely, with a sharp increase in penetrating particles roughly 30 min after the CME was detected by LASCO. There is no clear shock signature in the particle data, but a large spike was recorded in the magnetic field pressure proxy on 29 October 2002 at 12:30 UT, which could be consistent with a shock from this event. Events 22 and 32 are the other examples of backsided events witnessed by the ER. SEPs and shocks were evident at both Earth and Mars for event 22, in an extended period of SEP activity lasting ~6 days. Event 32 was much weaker, which occurred during a period of low solar activity, and showed an enhancement in both penetrating particles and the magnetic pressure proxy. This feature has tentatively been identified as a possible shock, generated by a backsided CME occurring ~4 days earlier.

In the last example described in detail here, event 14 shows an intriguing case when a shock from a known CME impacted Earth and Mars nearly simultaneously. In this event SEPs from a CME/flare on 24 September 2001 from 10:00–10:30 UT are evident in ACE, GOES, and ER data (Figure 11). Event 26 in 2001 of Jian et al. [2006a] confirms the arrival of a shock at 20:05 UT on 25 September at Earth. Both the ER and the magnetic pressure proxy on MGS showed signs of a shock signature close to 20:08 UT on the same day, with the penetrating particle flux increasing by almost two orders of magnitude in less than an hour. The curvature of the shock may have played a role in its apparent arrival time at Earth and Mars. Interactions with

Figure 9. The Bastille Day event of 2000 as witnessed by spacecraft at Earth and Mars. During this time Earth and Mars are in conjunction (separated by ~174° in solar longitude). Despite this wide angular separation, the initial SEPs are visible at both Earth and Mars for this event. A shock impacts the Earth but not Mars.
high speed streams can also cause a shock to arrive nearly simultaneously at Earth and Mars [Falkenberg et al., 2011a].

8. Comparison with Mars Odyssey

[33] Recently Zeitlin et al. [2010] summarized solar particle event and GCR fluxes using multiple instruments on the Mars Odyssey spacecraft, including the Martian Radiation Environment Experiment (MARIE), gamma ray spectrometer (GRS), and high-energy neutron detector (HEND). The MGS data coverage begins in March of 1999, three years before MARIE measurements began, and enables measurements of significant events such as Bastille Day in July of 2000. From March of 2002 to mid-2006, our analysis covers the majority of the same periods of enhanced SEP activity listed in Zeitlin et al. [2010, Table 3]. To date there has been no detailed event comparison or cross-calibration of particle fluxes between the Odyssey results and the MGS/ER. However, the results summarized in Zeitlin et al. [2010] enable a few examples to be described here. During a quiet time interval in mid-2002, measurements from Odyssey indicate an integral GCR flux level of $\sim 0.133$ particles/cm$^2$-s-sr. This is close to ER and CRIS measurements of the proton flux, which varied between 0.13 and 0.14 particles/cm$^2$-s-sr during this period. Since the latter is for protons, the integral GCR flux implied by these measurements is about 10% higher when He and heavier ions are taken into account; thus the Odyssey and ER results for GCR flux agree to within $\pm 10\%$ during this time. Near the end of the MGS mission in mid-2006, the ER and CRIS measured an integral proton flux of 0.25/cm$^2$-s-sr, implying a total integral flux of $0.28$ particles/cm$^2$-s-sr for GCRs. The Gamma Ray Spectrometer data on Odyssey detected $<0.2$ particles/cm$^2$-s-sr during this time, indicating a growing discrepancy with the MGS results as solar minimum is approached near the end of cycle 23.

Figure 10. Example of backsided event detected by MGS on 28 October 2002.
Zeitlin et al. [2010] directly compared an estimate for the flux seen by the ER with the scintillator channels of the HEND for the large Halloween event on 28 October 2003. Their analysis normalized the ER flux levels by assuming a quiet time differential flux of $0.1 \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ eV}^{-1}$ for the ER background near this period. Using this normalization, the ER flux estimates they obtained were several orders of magnitude lower than HEND during the Halloween event. Our own analysis of this event using the particle detection mechanism outlined above and in the Appendix predicts somewhat better agreement. Assuming an average geometric factor of $\sim 47.7 \text{ cm}^2$, the initial SEP flux peaks at $\sim 250 \text{ particles/cm}^2 \text{ s sr} >30 \text{ MeV}$, or roughly a factor of $\sim 5$ lower than implied by HEND data. Differences in shielding and energy threshold could account for this level of discrepancy. A detailed comparison between Odyssey and MGS measurements of GCR flux and individual solar events remains an important task for future work.

9. Data Set and Modeling

The limitations of characterizing SEPs and ICMEs from a single location are well known, and this has been the motivation for many groups to use multispacecraft observations whenever possible. Past efforts included measurements from Helios 1 and 2, Pioneer 10 and 11, and Voyager 1 and 2, among others [Dryer, 1987; Dryer and Shea, 1986]. One of the more obvious applications of multipoint observations of ICMEs is the ability to validate models of shock propagation velocity. Limb events may be particularly advantageous in this case. When Mars leads or lags the Earth by $\sim 90^\circ$, the initial CME velocity is more aligned with the plane-of-sky direction and thus projection effects...
are minimized [Gopalswamy et al., 2001; Lindsay et al., 1999]. This geometry thus provides for the most accurate initial velocity estimate possible, while the actual transit time can be measured directly through detection a Mars. The ER data set covers over 2.5 orbits of Mars around the sun, and thus provides a number of opportunities to characterize shock propagation in this geometry. For Earth-Mars opposition when each planet is on or near the same region of the Parker spiral, ER data can provide an extra data point at ~0.4 AU distance and also in some cases detect shock width and curvature effects.

[35] In the area of SEP propagation, multipoint measurements at different points in the Parker spiral may help resolve different particle acceleration mechanisms in the case of gradual versus flare accelerated events. The distinction between these two mechanisms has become less apparent, as some impulsive SEP events have been shown to be accompanied by smaller CMEs [Kahler et al., 2001; Reames, 2002], while some major CMEs show signs of both types of acceleration [Cane et al., 2003]. From a single location, distinguishing between these two types of acceleration relies on temporal arguments using the time-intensity profile in addition to detailed measurements of SEP composition. Observations from multiple locations spread out in solar longitude add a spatial discriminator to these events, as different observers are connected to different parts of the acceleration region. Shock accelerated particles should appear more broadly across field lines as the shock expands, while flare-accelerated events will be more localized to regions of direct magnetic connection to the observer [Cane et al., 1986; Reames, 1999b; Ruffolo, 2002]. The analysis of the time-intensity profiles using ER data combined with other locations may help separate which acceleration mechanisms are at work, from shocks, flares, or some combination of both, for a given event.

[36] Time intensity profile comparisons between Earth and Mars can also provide supporting evidence for the location of CME source regions. In looking at the LASCO catalog for the CME shown in Figures 2 and 7, it would be tempting to associate this event with a coincident C7.2 flare at S18°W42° on 8 January 2002 at 17:54 UT. However, there was no dimming of this flare during the CME expansion, nor were any SEPs detected by ACE prior to the shock arrival as would be expected for an event originating to the west. With Mars trailing the Earth by ~77° at this time, the ER detected pre-shock SEPs a few hours into 9 January 2002, which would be highly unlikely if the point of origin was to the west as seen from Earth, since this would put the source region well behind the west limb as seen from Mars. However, a source location closer to the central meridian as seen from Mars (or the east limb as seen from Earth) could produce SEPs at Mars prior to shock arrival as shown in the ER data. The data from the ER for this event are thus consistent with the observations of an east limb component by LASCO, and the conclusions of Cane et al. [2006], who associated this event with a C9 flare at NE100 as opposed to the C7.2 flare farther to the west.

[37] While the physical mechanism for the detection of energetic particles in the ER instrument was not understood prior to this work, ER results have nonetheless already been used to assist in model validation for ICME and SEP propagation where multipoint measurements are advantageous [Falkenberg et al., 2011a, 2011b]. Falkenberg et al. [2011b] used data from GOES and MGS to refine the initial speed and direction of several CMEs in November of 2001 for use in the ENLIL ICME propagation model. This work underscored some of the difficulties in predicting the impact of a CME at Mars when observed from Earth. In addition to the potential issues in using initial velocity estimates from plane-of-sky speeds, the spatial extent and direction of CME can be difficult to ascertain from the vantage point of Earth. As one example of this, they determined that event 16 in Table 1 was more intense at Mars than observations from Earth implied. Although initially classified as a halo event, MGS data combined with ENLIL model results suggest that this event just grazed the Earth while the impact at Mars was much more direct. In looking at a larger number of ICME shock arrivals in 2001 and 2003, Falkenberg et al. [2011a] determined that in general the times between shock arrivals at Earth and Mars were shorter than expected; explanations include the possibility that these events were more directed at Mars than Earth, and were influenced by interplanetary conditions such as high speed streams.

[38] To facilitate future work, a data set has been made publicly available for use in ongoing SEP and ICME modeling efforts such as the Earth-Moon-Mars Radiation Exposure Module (EMMREM), ENLIL, HAFv.2 and others. This data consists of summary plots of observations for both Earth in Mars, and a data file containing count rates of the three highest energy channels of the ER. The summary plots are stored as Portable Document Format (PDF) files in a similar format as shown in Figures 6–11, and cover periods of enhanced counts in the upper energy channels from May 1999 to August of 2006. The ER count rate data is averaged into 5 min time bins, and consists of the 6, 9.9, and 16.1 keV energy channels contained in an ASCII file throughout the period shown in Figure 3. From the count rate data, additional selection criteria in terms of uniformity in count rate across these energy channels and knowledge of solar events from other measurements can be applied to isolate SEP events and shocks. Additional features consistent with ICME arrivals may also reveal themselves in the ER data when combined with the magnetometer data, provided that the role of the magnetic pressure proxy in the identification of an ICME can be justified. Many events in the ER data set lack ESP peaks, but do possess sudden increases in the magnetic pressure proxy whose timing and amplitude suggest they may be the result of ICME shocks. The direct connection between increases in the pressure proxy and shocks has yet to be fully established, although in the cases presented here, they accompanied all but one of our shocks identified using ESPs. The difficulty lies in the fact that there appear to be other causes of an increase in the magnetic pressure proxy, for example SIRs or CIRs. Thus while an increase in
the pressure proxy almost always accompanies ESPs, the converse is not necessarily true. Additional measurements or inferred plausibility through modeling may be necessary to definitively associate pressure proxy features with ICMEs. If these increases in the pressure proxy can be related to the presence of ICME shocks, the database of shock arrivals in the ER data set would expand significantly.

10. Conclusion

[39] Using supporting data from ACE combined with previous laboratory experiments, we have determined the physical mechanism by which the ER instrument on MGS recorded the presence of particles with sufficient energy to penetrate the instrument housing. Flux estimates are accurate to within 10% for higher energy particles in GCRs. The characterization of SEP fluxes may be possible for some individual events, but in general remains uncertain due to shielding effects, pitch angle anisotropy, and the presence of electrons in addition to ions. The method of energetic particle detection we describe in the case of the ER should also apply to similar electrostatic analyzer designs such as the Aspera-3 instrument on Mars Express and the nearly identical ER on the Lunar Prospector mission. Using knowledge of the nature of the ER background versus SEP-enhanced count rate levels, we applied selection criteria to isolate events consistent with the presence of penetrating energetic particles. Of these, a subset of 41 events was definitively associated with an individual or group of flares/CMEs, and included observations over the full range of solar longitudes between Earth and Mars. A data set of these events has been made available to the community in order to facilitate the identification of new solar-related and other disturbances and to act as a validation tool for the numerous CME and SEP models currently under development. Improved estimates of absolute flux levels for individual solar particle events may be enabled by detailed comparisons with results from Mars Odyssey and other measurements of SEP energy spectra.

Appendix A: Response of MCPs to Energetic Particles

[40] As described in the main text, the efficiency of the ER MCP for energetic particle detection depends on a potentially large number of collisions (>100) with the individual MCP channel walls, with a small probability of a \(\delta\)-ray emission per collision (i.e., <1%). Given low probabilities per interaction, Poisson statistics are appropriate, where the probability of \(k\) events occurring can be expressed as:

\[ P(k, \lambda) = \frac{\lambda^k e^{-\lambda}}{k!} \quad (A1) \]

where \(\lambda\) is the expected probability for a single event. In this case, \(\lambda = p_w N\), where \(p_w\) is the probability per channel wall of emission and \(N\) is the total number of channels crossed by an incoming particle. The probability of one or more events being generated becomes \(P(k > 0, \lambda) = 1 - P(0, \lambda)\). It is easy to show that for a given MCP \(L/d\) ratio, the number of channel walls crossed becomes \(N = \frac{L/d}{\cos \alpha}\) where \(\alpha\) is the angle between the incident particle trajectory and the MCP plane (Figure 4a). Here we ignore the MCP bias angle \(\alpha'\), which was oriented in different directions throughout the MCP plane in the ER design, and thus averages to zero when an ensemble of events is considered. The probability for electron emission per channel wall will in general increase with the penetrating particle path length through each channel wall, which is proportional to \(\sim 1/\cos \alpha\). Denoting the probability of emission at normal incidence (\(\alpha = 0^\circ\)) to a channel wall as \(p_w\), then the probability of emission at incident angle \(\alpha\) is \(p_{\alpha} = p_w/\cos \alpha\). In the case of an MCP, the overall efficiency then becomes:

\[ f(\alpha) = 1 - e^{-k/\sin \alpha} \quad (A2) \]

where \(k = p_w(L/d)\). In the experiments conducted by Oba et al. [1981], particles entering at a 45° angle of entry had a probability of emission per channel wall of 0.6%. For an MCP \(L/d\) of \(\sim 80\), \(k/\sin \alpha\) is \(\sim 0.48\), yielding a 38% chance of one or more electrons being emitted during the traversal in equation (A2). The overall MCP efficiency is governed by the competing effects of the total number of channels crossed versus the path length within each of the channel walls. Shallower angles of incidence with respect to the MCP plane will cross more channels, but will have lower path lengths within each channel wall due to a more normal angle of incidence with respect to the wall orientation. A particle with near normal incidence to the MCP plane will cross fewer channels but have longer path lengths within each channel wall. Figure 4 summarizes this spatial dependence as a function of entry angle, corresponding to a changing \(\lambda = p_w(L/d)/\sin \alpha\) in equation (A2). In general, the effect of crossing multiple channel plate walls becomes more important than the path length within each wall, such that maximum efficiencies occur for shallow angles of impact with respect to the MCP plane, and reaches its minimum value for normally incident particles. Thus the MCP response to energetic penetrating particles is necessarily directional.

[41] The efficiency of each MCP channel wall in terms of secondary electron production per incident energetic particle can be also be justified from a simple theoretical standpoint using standard Bethe-Bloch formalism as well as empirical data on the range of electrons in materials. For thin targets with respect to the penetration depth of minimum ionizing, energetic primaries, it is straightforward to show that the probability for the primary energetic \(\delta\)-rays to escape to the material surface before re-absorption is small but non-negligible [Leroy and Rancoita, 2009]. The practical range of electrons with energies less than \(\sim 3\) MeV is approximated by:

\[ R_p = 0.412E^s \quad (A3) \]

Where \(E\) is the electron kinetic energy in MeV, \(s = 1.265 - 0.0954\ln E\), and \(R_p\) is in units of g/cm\(^2\). Assuming a density of
~4 g/cm³ for MCP glass [Wiza, 1979], electrons ≥27 keV are capable of escaping through 3 μm of MCP material, which represents a typical channel wall thickness. For a point midway through the MCP channel walls (~1.5 μm) this energy threshold reduces to ≥19 keV. For energy loss small compared to the incident particle energy, the probability that an incoming ion generates a δ-ray of energy greater than $W \delta$ in a material is given by:

$$P_\delta = 0.1535x \frac{\rho Z}{A/\beta^2} \left( 1 \frac{1}{W_\delta} - \frac{1}{W_m} \right)$$

(A4)

where $x$ is the distance traversed into the target in cm, $\rho$ is the target density in g/cm³, $Z/A$ is the ratio of atomic number to mass for the target nuclei, $\beta$ is the relativistic speed of the incoming particle = $v/c$, $W_\delta$ is the outgoing electron energy, and $W_m$ is the maximum energy that can be imparted to an electron by the incident particle, each in MeV. As an order of magnitude estimate, we assume an MCP wall thickness of ~3 μm, an entrance angle of entry of ~45°, and that the resulting δ-ray would traverse an average distance of ~1.5 μm prior to escape. For a high energy ($\beta \sim 1$) particle, this yields $P_\delta \sim 0.65\%$ for the production of a δ-ray with $W_\delta > 19$ keV. In reality, this probability will vary depending on the geometry of particle entry and the preferential direction for δ-ray emission. Equation (A4) does not take into account the emission of lower energy secondary electrons, which also remains possible, however the low energy threshold for δ-ray escape indicates that a large fraction of the emitted electrons are likely the primary δ-rays. This approximate result is also of the same order as the efficiency determined by Obi et al. [1981] for each MCP channel wall ($P_\delta \sim 0.6\%$). As a check on this interpretation of the sensitivity of the ER MCP to energetic protons, we used GEANT simulations to show that $\beta \sim 1$ proton incident on 3 μm thick MCP glass over a variety of entry angles generates electron emission with probabilities ranging between ~0.3–0.9% from both sides of the channel wall, which encompasses the experimental and analytic values described above. At lower energies, the probability predicted by equation (A4) will increase somewhat due to the presence of the $1/\beta^2$ term. For example, the probability of emission for 1 GeV and 100 MeV protons for a 45° angle of entry becomes 0.84% and 3.2%, respectively. As incident particle energies decrease below ~10 MeV, the maximum kinetic energy $W_m \sim 2mc^2(\beta^2)$ that can be transferred to the δ-ray becomes comparable to $W_\delta$, thus increasing the importance of the $1/W_m$ term and sharply reducing $P_\delta$, as fewer δ-rays have sufficient energy for escape.

A1. Calculation of Geometric Factor and MCP Efficiency

For GCR energies the ER MCPs are treated as a single isolated plane of area $A$. The angles $\theta$ and $\phi$ are defined in standard spherical coordinates, and the vector $\hat{a}$ normal to the MCP plane is oriented along the $y$-axis in order to facilitate a more convenient subtraction of the FOV obscured by Mars (Figure A1). At the nominal mapping orbit altitude of ~400 km, Mars obscures a cone with half-angle $\theta_0 = 63^\circ$ in the angle $\theta$ covering the nadir-facing hemisphere. In general, without obstructions and assuming the detector is sensitive to particles arriving at both sides of the MCP plane, the geometric factor $G_{ER}$ may be calculated using:

$$R = jG_{ER} = \int_{\phi = 0}^{2\pi} \int_{\theta = 0}^{\pi} \int j \sin^2 \theta \sin \phi \, d\theta \, d\phi \, dA,$$

(A5)

where $R$ is the count rate at the detector, and $j$ is the flux of incident particles, which are assumed to be isotropic. We omit any integration over energy, under the assumption that this geometric factor represents sensitivity to all energies above the threshold of detection for the ER. Equation (A5) yields the standard result of $G = 2\pi A$ when integrated over all angles. In the case of the MCPs on the ER instrument, the integration over $\theta$ should exclude the area obscured by Mars, starting at $\theta_0 = 63^\circ$, and also include the angular dependence of the MCP sensitivity to incoming...
energetic particles described by equation (A2). Thus an MCP efficiency function can be defined:

\[ f(\alpha) = f(\theta, \phi) = 1 - e^{-k \sin(\theta, \phi)}, \quad (A6) \]

where the incident angle \( \alpha \) is a function of the angles \( \theta, \phi \) in spherical coordinates, and represents the angle between an incoming particle and MCP plane as in Figure 4. Including the efficiency function and changing the limits of integration to exclude the FOV obscured by Mars, the rate calculation becomes:

\[ R = jG_{ER} = \int \int_{A} jf(\theta, \phi) \sin^2 \theta \sin \phi d \theta d \phi d A. \quad (A7) \]

Equation (A7) was numerically integrated over a range of plausible efficiencies with and without obscuration by Mars (i.e., \( \theta_o = 63^\circ \) and \( 0^\circ \)). In all cases, Mars accounts for a \( \sim 23\% \) loss of incident flux; thus we assume that the ER measures \( 77\% \) of the total flux compared to a detector free of planetary obscuration such as CRIS on ACE.

[45] The factor \( G_{ER} \) can be determined directly by comparing the ER background count rate data to CRIS proton results. Prior to this, some estimation of the contribution of heavier ions to the GCR flux, comprised mainly of He, needs to be made. The detection efficiency for MCPs to heavier ions will be at least 4 times greater than for protons, due to the dependence of the energy transfer process on the square of the ion charge in this regime. Based on the measurements by Mosher et al. [2001] we initially assumed efficiencies of order \( \sim 80\% \) for alphas and heavier particles, and subtracted counts from these particles from the ER rate data prior to comparison with the CRIS proton flux. Using these corrected counts from the ER MCP, in which both the obscuration from Mars and the contribution of particles with \( A > 2 \) have been accounted for, the ER count rate \( R \) was sorted from a minimum to a maximum and a least squares fit was performed with sorted CRIS proton flux data. The result is a constant of proportionality and a least squares fit was performed with sorted CRIS data as implied probability corresponding to \( 1/4 \) of 23 of 23

The geometric factor \( G_{ER} \) is given by \( 1/a_1 \) in equation (A8), yielding \( 33.11 \pm 0.34 \) cm\(^2\)s\(^{-1}\)sr. Equation (A8) implies a non-negligible DC offset in the ER count rate data, corresponding to \( 1/a_1 \sim 2.5 \) counts/s throughout the ER energetic particle data set. The origin of this noise is at present unknown, although a few likely candidates exist, including dark noise and occasional electrons at 15–20 keV energies that were selected through the electrostatic analyzer optics. Given the excellent agreement between the fit to the CRIS and MGS ER data, the origin of this constant background is unlikely to be of importance for the overall efficiency of the MCP detector to energetic penetrating particles and is hereafter ignored.

[44] The derivation of \( G_{ER} \) allows for an estimation of the per-wall probability of \( \delta \)-ray emission for the ER MCP through the function \( f(\theta, \phi) \) in equation (A7). This quantity is useful for a comparison with the experimental results obtained by Oba et al. [1981], as well as the simple theoretical expression (equation (A4)) above. To make this determination, the pulse height characteristics of the amplified MCP signal are particularly important to consider in estimating the degree to which MCPs are sensitive to penetrating particles. Under normal operation of the instrument, after energy-selection through the analyzer section the incoming electrons generate secondary electrons near the top of the MCP assembly. The resulting electron cascade thus utilizes the majority of the channel length for amplification, producing a well-defined peak in the pulse height response. For energetic particles penetrating the MCP channel walls the situation is somewhat different, in that the probability of electron emission is small during each encounter with a channel wall, such that these interactions will occur over a range of depths in the MCP. The deeper within the MCP stack the \( \delta \)-ray generation occurs, the less channel length remains available for amplification, resulting in smaller charge clouds at the anode beneath the MCP and correspondingly lower pulse heights. When these pulse heights become less than the discriminator settings of the electronics, they will not be counted and thus these events will go undetected. Despite this issue, the pulse height distribution of minimum ionizing particles in MCPs is in general well separated from intrinsic backgrounds such as that produced by dark noise, caused by the decay of \( ^{40}\text{K} \) within the MCP glass [Siegmund et al., 1989, 1988]. The ER instrument discriminator levels were set to the highest levels possible in order to reject background noise, such that less than 5% of the desired signal counts from low energy (<20 keV) electrons would be inadvertently excluded. With these discriminator settings, an incident penetrating particle that bypasses the first MCP and produces a \( \delta \)-ray only in the second MCP in the chevron stack in the ER would be insufficient to generate a detectable charge pulse. Hence the lower MCP is excluded from the calculation of the ER sensitivity to GCRs and SEPs. The question then becomes what is the maximum distance an energetic particle can penetrate into the first MCP before triggering an event that has sufficient amplification through the second MCP for detection. This is difficult to model in complete detail, however using typical channel plate properties this point can be reasonably constrained to be somewhere between 50% to <100%
of the first MCP plate thickness (see for example [Fraser, 1983]). The latter figure represents an absolute upper limit, since this implies that δ-rays produced near the bottom of the first MCP would trigger sufficient amplification in the lower MCP for a detectable pulse. With this assumption, we arrive at a range of $p_w \sim 0.7\%$–1.4% probability of a δ-ray production at each channel wall for 45° incidence. The lower bound of this estimate is within ~15% of the value experimentally derived by Oba et al. [1981], where incident protons of ~7 GeV/c were used. Equation (A4) indicates what we can expect about this difference due to the fact that GCR fluxes peak at ~1 GeV and will thus be about 15% more efficient in low energy δ-ray production, making the lower limit derived for the ER efficiency essentially consistent with the results from Oba et al. [1981]. In the Oba et al. study, discriminator levels were set to avoid unrelated electronics noise but also to maximize the detection of the pulse height spectrum characteristic of minimum ionizing particles, and were thus likely much lower than the more conservative settings applied in the MGS ER. Hence their estimate of a ~0.8% probability of δ-ray emission per channel is also a lower limit, since they are also failing to detect some percentage of interactions that occur lower in the MCP stack with pulse heights below threshold. However, their estimate is probably much closer to the true value, given the lower discriminator settings. Hence in the range of per-wall probabilities derived for the ER, we favor the lower end (~0.7%), implying that the majority of the volume in the first MCP of the ER was involved in the detection process.

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References


