Observations of Suprathermal Electrons in Mercury’s Magnetosphere during the Three MESSENGER Flybys

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Abstract

In 2008 the MESSENGER spacecraft made the first direct observation of Mercury’s magnetosphere in the more than 30 years since the Mariner 10 encounters. During MESSENGER’s first flyby on 14 January 2008, the interplanetary magnetic field (IMF) was northward immediately prior to and following MESSENGER’s equatorial passage through this small magnetosphere. The Energetic Particle Spectrometer (EPS), one of two sensors on the Energetic Particle and Plasma Spectrometer instrument that responds to electrons from ~35 keV to 1 MeV and ions from ~35 keV to 2.75 MeV, saw no increases in particle intensity above instrumental background (~5 particles/cm$^2$-sr-s-keV at 45 keV) at any time during the probe’s magnetospheric passage. During MESSENGER’s second flyby on 6 October 2008, there was a steady southward IMF, and intense reconnection was observed between the planet’s magnetic field and the IMF. However, once again EPS did not observe bursts of energetic particles similar to those reported by Mariner 10 from its March 1974 encounter. On 29 September 2009, MESSENGER flew by Mercury for the third and final time before orbit insertion in March 2011. Although a spacecraft safe-hold event stopped science measurements prior to the outbound portion of the flyby, all instruments recorded full observations until a few minutes before closest approach. In particular, the MESSENGER Magnetometer documented several substorm-like signatures of extreme loading of Mercury’s magnetotail, but again EPS measured no energetic ions or electrons above instrument background during the inbound portion of the flyby. MESSENGER’s X-Ray Spectrometer (XRS) nonetheless observed photons resulting from low-energy (~10 keV) electrons impinging on its detectors during each of the three flybys. We infer that suprathermal plasma electrons below the EPS energy threshold caused the bremsstrahlung seen by XRS. In this paper, we summarize the energetic particle observations made by EPS and
XRS during MESSENGER’s three Mercury flybys, and we revisit the observations reported by Mariner 10 in the context of these new results.

Keywords: Mercury, Magnetosphere, Energetic particles, MESSENGER
1. Introduction

The Mariner 10 (M10) spacecraft flew by Mercury three times in 1974 and 1975 and made measurements inside Mercury’s magnetosphere during its first and third (M10-I and M10-III, respectively) encounters. The M10 in-situ measurements not only showed that Mercury possesses an intrinsic magnetic field (Ness et al., 1974), they also revealed substorm-like energetic particle bursts (Simpson et al., 1974) within the magnetosphere. However, ambiguities in the interpretation of the M10 energetic particle detector data were pointed out by Armstrong et al. (1975, 1979). In particular, there are difficulties extracting sufficient energy to accelerate highly repetitive bursts of high-energy (>600 keV) electrons in Mercury’s small magnetosphere (Russell et al., 1988). Alternative scenarios to explain the source and acceleration of these reportedly high-energy electrons were put forward by Eraker and Simpson (1979), Baker (1986), and Luhmann et al. (1998). A summary of M10 energetic particle observations and their interpretation has been given by Wurz and Blomberg (2001). From the limited set of in-situ data obtained by M10, it is safe to conclude that the identity of the particles measured remains uncertain.

Given the controversy over the interpretation of the M10 particle observations, new measurements are needed to gain insight into the particle population in Mercury’s magnetosphere. NASA’s MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft flew by Mercury on 14 January 2008 (M1), 6 October 2008 (M2), and 29 September 2009 (M3) to perform gravity while en route to a scheduled insertion into orbit about the innermost planet in March 2011 (Solomon et al., 2007). During these three flybys, the spacecraft’s particle and field instruments returned the first direct measurements of Mercury’s magnetosphere in the 33 years since the last M10 encounter.
At the times of MESSENGER’s three flybys, the component of the interplanetary magnetic field (IMF) normal to Mercury’s orbital plane exhibited all three possible orientations: steadily northward (M1), steadily southward (M2), and varying between north and south (M3). As a result, Mercury’s magnetosphere exhibited markedly different plasma and magnetic field signatures during the three encounters (Slavin et al., 2009a, 2009b, 2010). The Energetic Particle Spectrometer (EPS), one of two sensors that comprise the Energetic Plasma and Particle Spectrometer (EPPS) instrument (Andrews et al., 2007) on the MESSENGER spacecraft, did not detect any >35 keV electron and ion fluxes above instrument background during any of the three flybys. This finding contrasts with what was originally reported from measurements made by the M10 particle instrument during M10-I. Nonetheless, measurements by MESSENGER’s X-Ray Spectrometer (XRS) are here interpreted to be indicative of low-energy (~10 keV) electrons impinging on its detectors during the three flybys.

The purpose of this paper is to describe the response of the EPS sensor during all three flybys through the magnetosphere and correlate these with the observations reported by MESSENGER’s Magnetometer instrument that delineated the magnetospheric topology. We then describe and model the XRS sensor responses and deduce the electron spectrum that resulted in the detection of X-ray photons. Finally, we revisit the observations reported by Mariner 10 in light of these new results.

2. The MESSENGER Energetic Particle and X-ray Spectrometers

The EPPS package on MESSENGER measures both the in-situ plasma composition and energetic particles (Andrews et al., 2007). EPS measures the energy, angular, and compositional distribution of the high-energy components of the in-situ electrons (> 35 keV) and ions (> 5...
keV/nucleon), and the Fast Imaging Plasma Spectrometer (FIPS) measures the energy, angular
distribution, and composition of the low-energy ion population.

The EPS is a time-of-flight (TOF) spectrometer with two main components: a TOF section
with a 6-cm flight path and a solid-state detector (SSD) array. Particles enter the system through
a collimator that delimits the look direction. They then transit a set of thin composite foils and
strike the SSD array at the end of the TOF section. Secondary electrons generated by the
particles (mostly ions) as they transit the foils are focused and detected by a set of microchannel
plates (MCPs). Hence, ion composition can be measured for H to Fe from ~35 keV to ~3 MeV
with the TOF section. Unfortunately, after launch the MCP voltage could not be raised to its
nominal operating value in order to measure the TOF values. Hence, ion composition data from
EPS have never been realized.

Nonetheless, the EPS SSD array at the back of the TOF section is operating nominally, so
total ion and electron counts can be measured by EPS. The EPS SSD array uses 500-µm-think
ion-implanted silicon solid-state detectors to measure the total energy of a particle; a thin layer
(1-µm) of aluminum on the top of the detector discriminates the low-energy ion from the
electrons. An electron that has energy higher than the threshold (~35 keV), however, will deposit
energy in both the ion and electron SSDs. There are six parallel electronics signal-processing
chains dedicated to the ion detectors and six parallel electronics signal-processing chains
dedicated to the electron detectors. Hardware counters from separate discriminators provide a
measure of whether particle pile-up is occurring (Andrews et al., 2007), a problem identified
with the M10 detectors in the presumed high-flux environment during that flyby (Armstrong et
al., 1975). Indeed, data from MESSENGER’s Earth flyby showed that by using both the fast and
shaped discriminator measurements the EPS was not subject to saturation even in the most intense regions of the inner radiation belt.

The X-ray Spectrometer (XRS) on MESSENGER is designed to measure the soft X-ray fluorescence (1-10 keV) from Mercury induced by solar X-ray illumination of its surface. The XRS instrument consists of two major units, a silicon-PIN solar monitor mounted on the spacecraft sunshade that measures the solar X-ray flux and three gas proportional counters (GPCs) that are mounted on the spacecraft nadir-pointing deck and designed to detect fluorescence from Mercury’s surface (Schlemm et al., 2007). A Be-Cu collimator restricts the field-of-view (FOV) of the GPC unit to 12°. The entrance windows of two of the GPCs are covered with thin foils of Mg (4.5-µm) and Al (6.3-µm), respectively, to allow separation of the low-energy fluorescence lines of Mg, Al, and Si. As will be discussed below, during the three Mercury flybys, the XRS recorded signals, including fluorescence of the Mg and Al filters, which were almost certainly caused by interactions with electrons from the magnetosphere.

3. Observations

3.1. Extremely quiet solar conditions

Solar activity has been extremely low since late 2007, including the times of three Mercury flybys. The observed sunspot numbers in 2008 were at the lowest level since the beginning of space age (see http://www.swpc.noaa.gov/). Particle instruments on spacecraft throughout the heliosphere have reported minimal solar energetic particle intensities, whereas the galactic cosmic ray intensities are at their highest level in 50 years (http://science.nasa.gov/headlines/y2009/29sep_cosmicrays.htm). Hence, even though EPPS has
been on and taking data almost continuously since June 2007, no major solar energetic particle (SEP) events have been detected above the EPS background rate (~0.1 s\(^{-1}\)), with one exception. Two weeks before M1, on 31 December 2007, MESSENGER observed a solar flare that was seen at the same time in soft X-rays by the Geostationary Operational Environmental Satellite (GOES) system and classified on the basis of those observations to be at least C8. However, the event occurred beyond the eastern limb of the Sun from the point of view of GOES, and analysis of X-rays detected from this event by the MESSENGER XRS indicates a flare magnitude of M2 (Feldman et al., 2010). Profiles of intensity versus time for selected electron energy channels from EPS during this event are shown in Fig. 1. From timing and modeling, we conclude that the event was composed primarily of electrons and was also associated with solar neutrons as reported by the Neutron Spectrometer on MESSENGER (Feldman et al., 2010). Since the 31 December 2007 event, there have not been any other such events detected by MESSENGER, although several have been seen by the Advanced Composition Explorer (ACE) Electron, Proton, and Alpha Monitor (EPAM) at 1 AU. Typical intensities at ACE, however, were at least a factor of 10 lower than the equivalent EPS background of \(\sim 2 \times 10^3\) (cm\(^2\) s sr MeV\(^{-1}\)).

3.2. Modeling of solar wind conditions

As part of the United States’ space weather effort, the National Science Foundation (NSF) has established the Center for Integrated Space Weather Monitoring (CISM). The CISM program, together with the National Oceanic and Atmospheric Administration (NOAA) Space Weather Predictions Center (SWPC), produces space environment predictions for the inner heliosphere. Baker et al. (2009) presented CISM predictions for the Mercury space environment at the time of the first MESSENGER flyby. Relatively slow solar wind conditions (solar wind velocity \(V_{sw}\sim\)
400 km/s) were modeled, and predicted solar wind density values \((n \sim 60-70 \text{ cm}^{-3})\) were also moderate as shown by Baker et al. (2010).

### 3.3. EPS observations

An overview of the field and particle measurements during M1 is shown in Fig. 2. As detailed by Slavin et al. (2008) and Anderson et al. (2008), the generally northward IMF was unfavorable to substorm-like particle energization processes (see Baker et al., 1996). On the basis of magnetic field measurements from the MESSENGER Magnetometer (MAG) and plasma measurements from FIPS, there was little evidence for reconnection between the IMF and the planetary magnetic field during M1 (Slavin et al., 2009b).

Energy spectra of the energetic particles measured by the EPS detector (including both ions and electrons) before, during, and after the M1 magnetospheric passage are shown in Fig. 3a. There were no differences in the spectral shape among the three time periods. The geometric factor of each EPS SSD is small \((10^{-3} \text{ cm}^2 \text{-sr})\), with no noticeable foreground from the environment; the instrument measured only high-energy galactic cosmic rays \((> 10 \text{ MeV})\). High-energy cosmic rays will penetrate the instrument outer skin and deposit a minimum-ionizing energy in the SSD detectors as a broad peak around \(\sim 150 \text{ keV}\), as shown in Fig. 3.

During M2, MESSENGER’s trajectory was very similar to that during M1, with the spacecraft remaining nearly in Mercury’s equatorial plane, approaching the planet from the night side and exiting on the dayside dawn sector. Note that between M1 and M2, the EPS energy channels and background were changed (as seen in Figs. 2, 3 and 4), because a flight software change was uploaded to EPPS in August 2008 to enhance the sensor telemetry and improve the background. During M2, Mercury’s magnetosphere was noticeably different from its condition...
during M1. A steady southward IMF led to classic reconnection signatures; flux-transfer events (FTEs) were observed in the magnetosheath and a plasmoid and multiple traveling compression regions were observed in Mercury’s magnetotail (Slavin et al., 2009b). EPS and MAG measurements during M2 are shown in Fig. 4, and the particle energy spectra measured by EPS are shown in Fig. 3b. Surprisingly, other than the drop in particle intensity at closest approach due to the shadowing effect of the planet on cosmic rays, there was no burst of energetic particles detected by EPS similar to that reported by the M10 particle instrument. From this null result, and with the lowest energy channel on EPS covering 36-57 keV, we estimate that the ~ 45-keV electron intensity in Mercury’s magnetosphere was not more than 5 particles/cm²/s/sr/keV.

The third and final flyby of MESSENGER at Mercury occurred on 29 September 2009. Immediately prior to the encounter, the IMF displayed a strong field magnitude (~28 nT) and variable north-south orientation (Fig. 5). (No detection was possible during the outbound portion of the M3 trajectory because of the spacecraft safe-hold event.) Slavin et al. (2010) reported multiple episodes of loading and unloading of the planetary magnetotail once the spacecraft was inside Mercury’s magnetosphere, in a pattern qualitatively similar to substorm-like signatures commonly observed at Earth. A key signature of tail unloading during terrestrial substorms is the acceleration of energetic particles, but once again no acceleration signatures were seen by EPS up to closest approach (Fig. 5).

3.4. XRS observations

During all three flybys, the XRS measured several count-rate spikes within minutes of closest approach, both before (M1, M2, and M3) and after (M2) closest approach. The timing of four of these events is indicated in Figures 2, 4, and 5. Those occurring before closest approach are here
termed called M1-E1, M2-E1, and M3-E1. The event that followed M2 closest approach is termed M2-E2. The signatures of these four count-rate spikes clearly identify their origin as energetic electrons (~10-30 keV) interacting with the XRS detector material. Electron-induced fluorescence and bremsstrahlung are evident in the XRS gas proportional counters as shown in Fig. 6 and described in more detail below (see also Adler and Trombka, 1977 and Starr et al., 2000). Other increases in the XRS count rates seen during the two flybys, especially during M1, do not show fluorescence of the filter materials, have a very different spectral shape, and are most likely the result of increased photon fluxes originating from outside the XRS GPC detectors. For example, the Crab Nebula was in the XRS FOV during one such XRS count rate increase ~30 hours prior to M1, and modeling confirms that supernova remnant was the source of the observed X-rays. The source of the photon event following the M1 closest approach is not yet certain, but the galactic center was within the XRS FOV at this time, making it likely that this event, too, was from an astrophysical source. Only the four clearly electron-induced events near flyby closest approaches will be discussed here.

The XRS response to charged-particle interactions has been modeled and verified by measurements with the XRS engineering unit using the Potential Drop Accelerator at the Radiation Effects Facility (http://radhome.gsfc.nasa.gov/radhome/ref/GSFC_REF.html) of the NASA Goddard Space Flight Center. The XRS instrument response was modeled with the Monte Carlo N-Particle eXtended (MCNPX) code (Pelowitz, 2005). Spectra measured during the flybys are well modeled by kappa-function electron distributions impinging on the XRS Mg and Al filters, Be windows, and Be-Cu collimator (Christon, 1987). The peaks at low energy seen in the plots for the Mg- and Al-filtered detectors in Fig. 6 correspond to the K-alpha lines for those two materials, at 1.254 and 1.487 keV, respectively. The broad peak at higher energy
seen in all three detectors during the M2-E2 event is from the Cu K-alpha line at 8.048 keV, produced by electron interactions in the Be-Cu collimator. Modeled results are compared to the measured X-ray spectra during events M1-E1 and M2-E2 in Fig. 6. For event M1-E1, the electron incidence angle is modeled as 0°, while for the M2-E2 event the incidence angle is modeled as 6°. The electron incidence angle determines the relative intensity of the Cu line and was varied to obtain the best fit between model and data. Model parameters are listed in Table 1. The absolute electron fluxes derived from the models are shown in Fig. 7, and the model parameters are given in Table 1. These electron fluxes are generally consistent with those predicted by the empirical model of Mukai et al. (2004) at 0.31 AU. During the flybys the MESSENGER spacecraft was at about 0.3 AU. The solar wind density was ~60 cm⁻³, ~60 cm⁻³, and ~50 cm⁻³ during M1, M2, and M3, respectively (Baker et al., 2010).

The electron flux fit to the XRS data is consistent with the EPS upper limit at 45 keV for the three fluorescence events detected prior to closest approach (M1-E1, M2-E1, and M3-E1). However, for the second of the two M2 events (M2-E2), which followed closest approach, Cu Kα fluorescence at 8 keV from the Be-Cu collimator, clearly indicates the presence of a much higher flux of electrons at energies greater than 10 keV. A good match to the XRS spectra (right-hand panels of Fig. 6) requires that the inferred electron intensity at 45 keV be ~100 times higher than the EPS upper limit at 45 keV as indicated in Fig. 7. The difference between the two results can be explained by the different FOVs for XRS and EPS.

The XRS is mounted on the bottom deck of the spacecraft and has a conical 12° FOV along the spacecraft +Z axis, whereas the EPS has a fan-shaped FOV that looks away from the spacecraft sunshade along the spacecraft +Y axis (Fig. 8a) (Schlemm et al., 2007; Andrews et al., 2007). Only for event M2-E1 was the magnetic field orientation favorable for the simultaneous
observation of electrons by both EPS and XRS, but the estimated electron intensity inferred from the XRS measurement is below the EPS sensitivity level. However, during M2-E2, the measured local magnetic field vector was perpendicular to the XRS normal, which is necessary for XRS detection but very unfavorable for EPS to measure the short-duration electron event detected by XRS (Fig. 8a). This geometry also implies that the electron pitch-angle distribution was narrowly peaked near 90°, consistent with the modeled incidence angle (6°).

4. Reconciliation of the M10 and MESSENGER results?

During the first Mariner 10 flyby of Mercury, four high-energy (>300 keV) particle events during the encounter and a high-energy (>600 keV) proton event were reported (Simpson et al., 1974). For three of the four events, the time-intensity profiles had very sudden onsets, and the peak intensity levels were at least three orders of magnitude above interplanetary background levels (Simpson et al., 1974). However, no such high-energy particles were detected by MESSENGER during any of the three flybys.

There could be several factors that contribute to the differences in observations between M10 and MESSENGER. The energetic particle instrument on M10 was designed to measure high-energy electrons (>170 keV) and ions (>600 keV) (Simpson et al., 1977; Wurz and Blomberg 2001). Compared with the EPS, the geometric factor of the M10 instrument was large (14 cm²-sr versus 10⁻³ cm²-sr). Because of its large geometric factor, the M10 particle instrument was more susceptible to saturation from high-count-rate events at or below the energy threshold of the instrument. Armstrong et al. (1975, 1979) pointed out ambiguities in the data set that suggesting that the M10 particle instrument was responding to pulse pile-up from low-energy (>35 keV) electrons during M10-I. In contrast, EPS is not susceptible to pile up from high-count-rate
events (Andrews et al., 2007), and in any case, not even low-rate events above background (~5 particles/cm$^2$/s/sr/keV at 45 keV) events were seen during any of the three MESSENGER flybys.

During M1, M2, and M3, solar particle activity in the inner heliosphere was very low because of the extended period of minimal solar activity. During much of the cruise period from June 2007 up to M3, there were no SEP events detected by EPS except for the one on 31 December 2007 (Fig. 1). It is possible that the number of low-energy suprathermal particles available in the inner heliosphere (Mason, 2000) that could interact with Mercury’s magnetosphere and later be accelerated in situ (Baker 1986) was also very low. This situation could limit the intensity of high-energy particle population in Mercury’s magnetosphere (e.g., Baker, 1986), and with EPS small geometric factor, we could not measure at that level. Not only has the extended period of low solar activity limited SEP seed particles for acceleration, but the IMF field has also been extremely weak. From the magnetic field measured by MAG during M2, Slavin et al. (2009b) calculated a cross-magnetosphere electric potential of about 30 kV. Although not all types of magnetospheric charged-particle acceleration processes are limited by magnetospheric potential drop, this low cross-magnetosphere potential is consistent with the lack of particles having energies larger than 35 keV as observed in the EPS data.

Slavin et al. (2009b) deduced that Mercury’s magnetosphere is highly responsive to IMF orientation due to its small inertia. During the steady southward IMF at the time of M2, magnetic reconnection signatures (FTEs, plasmoids) were observed throughout the Mercury’s magnetosphere. However, no dipolarization was observed by the MESSENGER magnetometer during M2 (or M1 or, M3). In Earth’s magnetosphere, dipolarization is closely related to particle acceleration during substorm activity (Baker et al., 1996). We also note that the M10 data showed a strong field dipolarization in close conjunction with the energetic-electron events.
(Christon, 1987; Slavin et al., 1997). The lack of high-energy particles at Mercury during reconnection may be important in understanding particle acceleration processes at Earth. During M3, several substorm-like signatures were evident in the MAG data (Slavin et al., 2010). Although a spacecraft safe-hold event stopped measurements on the outbound portion of the trajectory, no energetic electrons with energies > 35 keV were detected above instrument background level during the entire inbound portion of the trajectory up to a few minutes before closest approach.

5. Conclusions

MESSENGER’s three passages through Mercury’s magnetosphere provided the first measurements of magnetospheric characteristics since the Mariner 10 flybys in 1974-1975. Mercury’s small magnetosphere is highly responsive to changes in IMF orientation and solar-wind conditions. During M1, the IMF was steadily northward, no reconnection signatures were observed from the Magnetometer during the flyby, and no energetic particles higher in energy than 35 keV were detected by the EPS. Because of the southward IMF, in contrast, multiple FTEs and plasmoid signatures were observed during M2. Surprisingly, EPS again made no direct detection of energetic particles having energies above 35 keV. From this null result we are able to place an upper limit on the electron intensity at 45 keV of ~5 particles/cm²/s/str/keV. During M3, the IMF was highly variable prior to spacecraft entry into Mercury’s magnetosphere. The MAG documented multiple tail-loading events similar to substorm-like signatures at Earth. However, a key signature of energetic-particle acceleration during substorm events at Earth, i.e., field depolarization, was absent at Mercury.
The XRS instrument on MESSENGER detected X-rays produced by low-energy electrons during both M1 and M2. We used a kappa distribution for the electrons to model the XRS instrument response and found good agreement between modeled absolute electron intensity and the upper limit given by EPS measurement except for one event during M2, for which the XRS-derived flux is 100 times higher than the EPS upper limit (Fig. 6). However, we found that the local magnetic field orientation during that XRS spike made detection of this short-duration electron event difficult to see with EPS, implying that the electron pitch-angle distribution was narrowly peaked near 90°.

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**Fig. 1.** A C8-class solar flare was detected by EPS on 31 December 2007, two weeks before the first MESSENGER flyby of Mercury. Energetic electrons from the flare are shown for three energy intervals.

**Fig. 2.** Overview of the energetic particle, magnetic field, and X-ray measurements during M1. During the passage of the spacecraft through Mercury’s magnetosphere, the IMF was generally northward. EPS has six look directions along the spacecraft Z-Y plane. Sectors 2 and 3 are the two look directions that are above and below the spacecraft X-Y plane, respectively, each covering 22° of the FOV. No energetic particles were detected by EPS at any time during the flyby. The XRS data, plotted in the bottom panel, show the single fluorescence event (M1-E1) detected. The three components of the in-situ magnetic field are plotted in Mercury solar orbital (MSO) coordinates: \(X_{MSO}\) points from the center of the planet to the Sun; \(Y_{MSO}\) is positive in the direction opposite to orbital motion; and \(Z_{MSO}\) is positive to the north and perpendicular to the Mercury’s orbital plane. Magnetospheric boundaries crossed include the inbound and outbound bow shock (BS) and magnetopause (MP); closest approach is denoted by CA. Radial distance from Mercury is measured in units of Mercury’s radius \(R_M\).

**Fig. 3.** Energy spectra determined by EPS before, during, and after the closest approaches for (a) M1, (b) M2, and (c) M3. The legends denote the time and radial distance when the 300-s-averaged spectra were taken during each flyby. There was a small change in the energy channels on EPS between the first two flybys, the result of new flight software uploaded to EPS in August 2008. Note, however, that the shape of the energy spectrum is essentially the same during each flyby. The energy peak near 150 keV for all flybys is the result of high-energy cosmic rays penetrating the solid-state detectors from all directions.

**Fig 4.** Overview of the energetic particle, magnetic field, and X-ray measurements during M2. Despite the steady southward IMF and the documentation of multiple reconnection events by the Magnetometer, no major energetic particle events were detected by EPS. The drop in particle intensity at closest approach corresponds to the shadowing effect of the planet on the cosmic-ray background. The XRS data show two electron-induced fluorescence events during the flyby (M2-E1 and M2-E2). For other labels see Fig. 2.

**Fig. 5.** Overview of the energetic particle, magnetic field, and X-ray measurements during M3. A spacecraft safe-hold event occurred a few minutes before closest approach, and no science data were collected after this event. The XRS data show a small electron-induced fluorescence event shortly before data flow was halted.

**Fig. 6.** Comparison of modeled (blue) and measured (red) XRS spectra for event M1-E1 (left column) and for event M2-E2 (right column). The incidence angles with respect to GPC normal for M1-E1 and M2-E2 are 0° and 6°, respectively. Parameters used to produce the modeled results are given in Table 1.

**Fig. 7.** Electron flux inferred from XRS measurements. The flux for M2-E1 (red curve) and for M1-E1 (not shown) are consistent with the EPS lower limit. The flux for M2-E2 at 45 keV is \(~100\) times greater than the EPS limit, indicated by the asterisk.
Fig. 8. (a) Sketch of the EPS and XRS FOVs in the spacecraft coordinate system. The XRS FOV is conical (12° full angle) along the spacecraft +Z direction, whereas the EPS has a fan-shaped FOV that looks away from the spacecraft sunshade along the +Y direction. The two FOVs do not overlap. Also shown is the orientation of the local magnetic field as measured by MESSENGER during event M2-E2. (b) XRS count rates on the three gas proportional counters during M2 and the angle (red) between the local magnetic field and the spacecraft Z-axis (or XRS collimator axis. The two electron-induced fluorescence events during M2 (M2-E1 and M2-E2) are indicated by vertical dashed lines.
Table 1. Parameters used to fit the XRS electron events detected during M1, M2 and M3.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Time of event (UTC)</th>
<th>Duration (s)</th>
<th>$N$  (electrons/cm$^2$-sr-s-keV)</th>
<th>Best-fit $K$</th>
<th>Best-fit $E_o$</th>
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<tr>
<td>M1-E1</td>
<td>14 January 2008</td>
<td>18:59:49</td>
<td>180</td>
<td>$1.35 \times 10^7$</td>
<td>8</td>
<td>0.7</td>
</tr>
<tr>
<td>M2-E1</td>
<td>6 October 2008</td>
<td>08:35:08</td>
<td>60</td>
<td>$5.39 \times 10^7$</td>
<td>8</td>
<td>0.7</td>
</tr>
<tr>
<td>M2-E2</td>
<td>6 October 2008</td>
<td>08:47:08</td>
<td>120</td>
<td>$3.06 \times 10^8$</td>
<td>7</td>
<td>1.0</td>
</tr>
<tr>
<td>M3-E1</td>
<td>29 September 2009</td>
<td>21:45:39</td>
<td>60</td>
<td>$3.85 \times 10^6$</td>
<td>8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Note: A kappa distribution (Christon, 1987) is assumed, where the electron flux is given by

$$j_e = N \left[ \frac{E}{E_o} \right] \left[ 1 + \frac{E}{K E_o} \right]^{-K-1},$$

and where $N$, $E_o$, and $K$ are the normalization factor, modal energy, and kappa, respectively.
Figure 1:
Figure 3:

(a) M1 Energy Spectrum

(b) M2 Energy Spectrum

(c) M3 Energy Spectrum
Figure 4:
Figure 5.
Figure 6
Figure 7.

Modeled Energetic Electron Flux Distribution

Electron Flux (particle/cm²/s/sr/keV)

- M2-E1
- M2-E2
- EPS Upper limit

Energy (keV)