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Astrophysical objects observed by the *MESSENGER* X-ray spectrometer during Mercury flybys

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ABSTRACT

The *MESSENGER* spacecraft conducted its first flyby of Mercury on 14th January 2008, followed by two subsequent encounters on 6th October 2008 and 29th September 2009, prior to Mercury orbit insertion on 18th March 2011. We have reviewed *MESSENGER* flight telemetry and X-ray Spectrometer observations from the first two encounters, and correlate several prominent features in the data with the presence of astrophysical X-ray sources in the instrument field of view. We find that two X-ray peaks, attributed in earlier work to the detection of suprathermal electrons from the Mercury magnetosphere, are likely to contain a significant number of events that are of astrophysical origin. The intensities of these two peaks cannot be explained entirely on the basis of astrophysical sources, and we support the previous suprathermal explanation but suggest that the electron fluxes derived in those studies be revised to correct for a significant astrophysical signal.

1. Introduction

On March 18th 2011 the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (*MESSENGER*) spacecraft became the first probe to orbit the planet Mercury. Launched on August 3rd 2004, *MESSENGER*'s trajectory included six gravity-assist manoeuvres: one flyby of Earth (August 2nd 2005), two of Venus (October 24th 2006 and June 5th 2007), followed by three flybys of Mercury, on January 14th and October 6th 2008, and September 29th 2009. A detailed description of the mission is given by Solomon et al. (2001, 2007). A review of the first Mercury encounter is given by Solomon et al. (2008), and a brief summary of the emerging view of Mercury after the three flybys is presented by Solomon et al. (2010).

The *MESSENGER* payload includes an X-ray spectrometer (XRS) for measurement of the planet's surface elemental composition. Schlemm et al. (2007) provide full details of the instrument, which is based around three separate Gas Proportional Counter (GPC) units filled with a P10 Argon–Methane mixture at 0.15 MPa (1.5 bar). In order to distinguish between characteristic X-ray lines of the major rock forming elements, and allow quantitative analysis of surface elemental abundances, one GPC carries a 4.5 μm-thick Mg filter, one has a 6.3 μm Al filter, and the third GPC is unfiltered.

The XRS was active during all the three Mercury flybys, and a number of X-ray emission features were observed during the encounters. Ho et al. (2011a) present a detailed analysis of several features of particular interest, attributing some to astrophysical sources, and some to the detection of suprathermal plasma electrons originating in Mercury's magnetosphere. Schriver et al. (2011) describe simulations and laboratory work on electron transport and acceleration in the Hermean magnetosphere and also interpret several X-ray features in the first and second flybys as the signature of suprathermal electrons. We give the times and durations of features considered by Ho et al. (2011a) (M1-E1, M2-E1, M2-E2 and M3-E1) in Table 1, and define four additional features (M1-B1, M1-B2, M1-B3 and M2-B1) which we have also considered in the present work.

Our analysis concentrates on the sensitivity of the XRS to bright astrophysical X-ray sources, and began as work conducted to support science planning activities for the Mercury Imaging X-ray Spectrometer (MIXS) instrument onboard ESA's *BepiColombo* mission to Mercury, with which the authors are affiliated (Fraser et al., 2010). A detailed analysis of *MESSENGER* spacecraft attitude and XRS instrument pointing during the flybys has been conducted, generating a model of the passage of known bright X-ray sources through the field of view (FOV) as a function of time. Using measured instrument sensitivity data and a simple treatment of the angular variation of the collimator transmission function, the instrument count rates expected from these sources have been calculated and compared with measurements from the XRS. The final column of Table 1 summarises our conclusion for the origin of each feature based on the present work.

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Table 1
XRS events considered in this work. Where features are discussed by Ho et al. (2011a) we adopt the *M[x]-E[y]* labels defined by the authors; we assign additional features a label of the form *M[x]-B[y]*. In each case *x* denotes the flyby number and *y* identifies the feature in the XRS dataset for that encounter. The final column summarises our findings for the origin of each feature (see Section 4 for details).

Event	Date	Start time (UTC)	Duration (s)	Origin
M1-E1	14 Jan 08	18:59:49	180	Electrons & astrophysical
M1-B1	14 Jan 08	19:20:12	300	Astrophysical
M1-B2	14 Jan 08	19:26:40	800	Astrophysical
M1-B3	14 Jan 08	19:41:00	1040	Astrophysical
M2-E1	6 Oct 08	08:35:08	60	Electrons & astrophysical
M2-E2	6 Oct 08	08:47:08	120	Electrons
M2-B1	6 Oct 08	08:57:10	220	Astrophysical
M3-E1	29 Sep 09	21:45:39	60	Insufficient data, no clear astrophysical source

In Section 2 we describe the reconstruction of instrument pointing and FOV location. Section 3 summarises the assumptions made in estimating the count rates generated by each object in the field, and in Section 4 we consider the major XRS features from the first two flybys in detail, identifying correlations between observed X-ray peaks and the presence of bright sources in the field of view. In two features (M1-E1 and M2-E1) we find evidence to suggest that significant numbers of astrophysical source photons are contributing to the recorded flux, in addition to the proposed suprathermal electron element which we also support. The available XRS data for Flyby 3 are less detailed due to a safe-hold event which took place during the encounter, and a lower level of analysis has been conducted for that event, which we cover briefly in Section 5.

2. Spacecraft telemetry and field of view direction

The XRS observations considered in this work were obtained as calibrated data records from the Planetary Data System Geosciences Node hosted by Washington University in St. Louis (http://pds-geosciences.wustl.edu/missions/messenger/xrs.htm). Count rates measured by the three GPC channels are provided with 60 s time resolution in the periods around the closest approach for each encounter. Full details of the calibrated data file structure are provided by Harshman (2010).

The attitude of *MESSENGER* was determined using the SPICE system produced by the NASA Navigation and Ancillary Information Facility (NAIF; Acton, 1996), which comprises spacecraft data and planetary ephemerides (both presented in data files referred to as "kernels") and the SPICE computational toolkit. For each flyby, the direction cosine matrix corresponding to the transformation between *MESSENGER* spacecraft body axes and J2000 coordinates was generated, for each attitude data point, with a temporal resolution of 0.36 s. The results were verified by combining these data with a spacecraft ephemeris in Mercury Solar Orbital coordinates, generated from the same kernels. In each case, the time, distance and location of the closest approach agreed with published values (Benna et al., 2010; Slavin et al., 2009). A list of the kernels used in this work can be found in Appendix A.

The *MESSENGER* XRS has a hexagonal FOV with a full-width-zero-maximum (measured from vertex to vertex) of 12°, and a boresight aligned with the spacecraft $+Z$ axis. The positions of the XRS FOV boresight and 6 perimeter points in the spacecraft frame are provided in the *msgr_xrs_v001.ti* kernel. These points were transformed into J2000 coordinates for each 0.36 s time interval, enabling precise mapping of the FOV onto the celestial sphere. In addition, spacecraft position and attitude data were imported into Analytical Graphics Inc.'s *Satellite Tool Kit* (STK)[1], and a sensor with the hexagonal FOV and orientation of the XRS instrument was reproduced to provide a time-resolved visualisation of the field position. The orientation of the FOV with respect to the planet in our model was found to be consistent with the state of the FOV_STATUS flag in the XRS data. This flag characterises the contents of the FOV, and has five states: (0) no part of the planet in the field; (1) planet filling the field, at least part of footprint in sunlight; (2) planet filling the field, no portion in sunlight; (3) only part of the field includes the planet, at least one part of which is in sunlight, and (4) only part of the field includes the planet, with the imaged portion in darkness. The times at which the FOV made contact with the planet and crossed the dawn/dusk terminator in our simulation were in agreement with the status of this flag.

[1] http://www.stk.com

3. Source population and count rate estimation

3.1. The bright source sample

The astrophysical X-ray sources included in this study were taken from the *ROSAT* All Sky Survey Bright Source Catalogue (Voges et al., 1999) (hereafter RASSBSC). Using the electronic version of the catalogue hosted by the Leicester Database and Archive Service (LEDAS), the one hundred brightest sources as measured by the *ROSAT* Position Sensitive Proportional Counter (PSPC) were identified. The right ascension and declination of each object (α_{2000},δ_{2000}) were extracted from LEDAS and imported as a point source into STK. For a 2 h period around the point of the closest approach for each flyby, the identity of any of the sources within the FOV was determined, and the angular position of the source with respect to the instrument boresight recorded with 1 s time resolution.

3.2. Source count rates

The *MESSENGER* XRS has a bandpass of 1–10 keV (Schlemm et al., 2007), significantly broader, and with a different effective area profile, than the 0.1–2.4 keV bandpass of the *ROSAT* PSPC (Pfeffermann et al., 1987). Given the wide range of source spectra represented in the RASSBSC sample, it is not possible to adopt a constant scaling factor to convert from *ROSAT* to *MESSENGER* count rates. We therefore estimated the photon event rates expected in the XRS by modelling source spectra with the XSPEC X-ray spectral analysis package, using best-fit spectral parameters found in the literature. The sources, their type and count rates from RASSBSC and the count rate predicted for the *MESSENGER* XRS (along with the references from which we obtained spectral parameters) are indicated in Table 2, while the spectral hardness of the sources is indicated by the Al:unfiltered and Mg:unfiltered channel count rate ratios shown in Fig. 2.