Planetary and Space Science 122 (2016) 13–25

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Calibration of the MESSENGER X-Ray Spectrometer

Richard D. Starr[a,*], Charles E. Schlemm II[b], George C. Ho[b], Larry R. Nittler[c], Robert E. Gold[b], Sean C. Solomon[c,d]

[a] Physics Department, The Catholic University of America, Washington, DC 20064, USA
[b] Space Department, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, USA
[c] Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA
[d] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA

ARTICLE INFO

Article history:
Received 13 August 2015
Accepted 4 January 2016
Available online 17 January 2016

Keywords:
Mercury
X-rays
MESSENGER

ABSTRACT

The X-Ray Spectrometer (XRS) that flew on the MESSENGER spacecraft measured X-rays from the surface of Mercury in the energy range ~1–10 keV. Detection of characteristic K_α-line emissions from Mg, Al, Si, S, Ca, Ti, and Fe yielded the surface abundances of these geologically important elements. Spatial resolution as fine as ~40 km (across track) was possible at periapsis for those elements for which counting statistics were not a limiting factor. Four years of orbital observations have made it possible to generate from XRS spectra detailed elemental composition maps that cover a majority of Mercury's surface. Converting measurements to compositions requires a thorough understanding of the XRS instrument capabilities. The ground and flight calibration measurements presented here are necessary for the reduction and analysis of the X-ray data from the MESSENGER mission.

1. Introduction

Mercury is the closest planet to the Sun, and because it is so close, it is difficult to study from Earth-based observatories. Its proximity to the Sun also makes it very challenging to send spacecraft to this tiny planet. Four decades ago Mariner 10 flew by Mercury, twice in 1974 and once in 1975, providing a wealth of new information about the planet (Dunne, 1974). Despite the many accomplishments of that mission, the limited observation time accumulated during the three flybys left much unknown about Mercury's geologic history and the processes that led to the planet's formation. Mariner 10 remained the only spacecraft to visit Mercury prior to observations by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft. MESSENGER is a NASA Discovery mission that was designed to fly by and orbit Mercury (Santo et al., 2001; Solomon et al., 2001). It was launched in August 2004. Following one Earth flyby (29 July 2005), two Venus flybys (23 October 2006 and 4 June 2007), and three Mercury flybys (14 January 2008, 6 October 2008, and 29 September 2009), the MESSENGER spacecraft entered into orbit about Mercury on 18 March 2011. At the beginning of the orbital mission MESSENGER's orbit was ~12 h long and highly eccentric, with periapsis at ~200–500 km altitude and apoapsis at ~15,000 km altitude. In April 2012, the apoapsis altitude was reduced to ~12,000 km and the orbital period was reduced to ~8 h. One of the instruments in the MESSENGER payload was the X-Ray Spectrometer (XRS), designed to determine the surface elemental composition of the planet by measuring solar-induced X-ray fluorescence (Schlemm et al., 2007).

XRS orbital operations began on 23 March 2011. X-ray fluorescence was routinely detected from the surface of the planet during both "quiet" Sun and flaring conditions whenever a sunlit portion of Mercury was within the XRS field of view. XRS can detect the characteristic X-rays of Mg, Al, and Si even during quiet-Sun conditions, but solar flares are required to produce measureable signals from elements at higher atomic number (Z) such as S, Ca, Ti, and Fe (Schlemm et al., 2007; Nittler et al., 2011). The XRS is sensitive to material within ~100 μm of the planetary surface.

Orbital X-ray fluorescence (XRF) experiments have flown on many planetary missions. X-ray spectrometers can provide surface composition measurements from any airless body. The first planetary XRF measurements were made by Luna 12 in 1968 (Adler et al., 1973) and then by the X-ray spectrometers on Apollo 15 and 16 (Adler et al., 1972a, 1972b). The Moon has been a frequent subject of XRF investigations, most recently by SMART-1 (Grande et al., 2007; Swinyard et al., 2009), SELENE (Okada et al., 2010), and Chandrayaan-1 (Narendranath et al., 2011; Weider et al., 2012a). X-ray spectrometers have also been flown to asteroids as part of the Near Earth Asteroid Rendezvous (NEAR) – Shoemaker

* Corresponding author. Tel.: +1 301 286 5073; fax: +1 301 614 6522.
E-mail address: richard.d.starr@nasa.gov (R.D. Starr).

http://dx.doi.org/10.1016/j.pss.2016.01.003
0032-0633/

mission (Trombka et al., 2000; Nittler et al., 2001; Foley et al., 2006; Lim and Nittler, 2009) and on Hayabusa (Okada et al., 2006).

MESSENGER is the latest planetary mission to include an XRF experiment as part of its science payload. Three gas proportional counters (GPCs) viewed the planet, and a Si-PIN detector mounted on the spacecraft sunshade viewed the Sun. The MESSENGER XRS incorporated an improved version of the NEAR – Shoemaker X-Ray Spectrometer design (Starr et al., 2000).

2. X-ray remote sensing

The primary source of X-ray fluorescent line emission from a planetary surface is the interaction of solar X rays with the surface (e.g., Yin et al., 1993). The most prominent fluorescent lines for the major elements Mg, Al, Si, S, Ca, Ti, and Fe are the K_α lines (1–10 keV). X-ray emission from the surface is strongly dependent on elemental composition, as well as the shape and intensity of the incident solar spectrum. The solar X-ray spectrum is not constant; it varies, on timescales of minutes to hours, in both intensity and slope. During quiet solar conditions, line emission from only a few light elements for which primary fluorescent lines are below 2 keV (Mg, Al, and Si) may be detected from orbit.

During periods of high solar activity the differential solar X-ray spectrum becomes much harder (i.e., stronger at higher energies) and more intense, enabling the measurement of heavier elements such as S, Ca, Ti, and Fe. Solar output is highly variable and may change by an order of magnitude or more within minutes. Greater solar activity yields better counting statistics within shorter integration times, and hence higher-resolution elemental abundance maps, especially for heavier elements such as Fe. Because of its variability, however, the Sun's output must be continuously monitored in order to obtain reliable results. An overview of X-ray remote sensing techniques for geochemical analysis has been given by Yin et al. (1993).

3. Instrument description

3.1. Planetary sensors

The MESSENGER XRS planet-pointing detector package included three large-area (10 cm^2) sealed gas proportional counters with thin (25 μm) Be windows. These three GPCs along with their measurement circuitry comprised the Mercury X-ray Unit (MXU). The MXU was situated within the MESSENGER payload adapter ring (Schlemm et al., 2007). Gas proportional counters were selected for the MESSENGER XRF experiment because of their flight heritage and large effective area. The large area provided the necessary sensitivity to achieve good counting statistics for short counting times (~minutes). The Be windows absorbed the lower-energy X-rays (below ~1 keV) that would otherwise dominate the detector count rate. Each counter was filled with P-10 gas (90% argon and 10% methane) to an absolute pressure of 1500 mbar. The bias voltage on each of the gas counters was ~1420 V during cruise and the first year of orbital operations. It was raised in the second year of orbital operations, as discussed below. The Be window was supported by a rectangular Be support structure. The

Table 1
Relative counting rate by cell number for the three GPCs.

Cell number				
1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
GPC1 – Mg filtered				
84%	90%	90%	90%	88%
94%	100%	98%	99%	97%
80%	88%	87%	87%	84%
GPC2 – Al filtered				
84%	93%	93%	93%	92%
91%	97%	100%	97%	93%
75%	82%	83%	82%	79%
GPC3 – Unfiltered				
82%	93%	94%	93%	90%
89%	99%	99%	100%	100%
74%	83%	86%	84%	84%

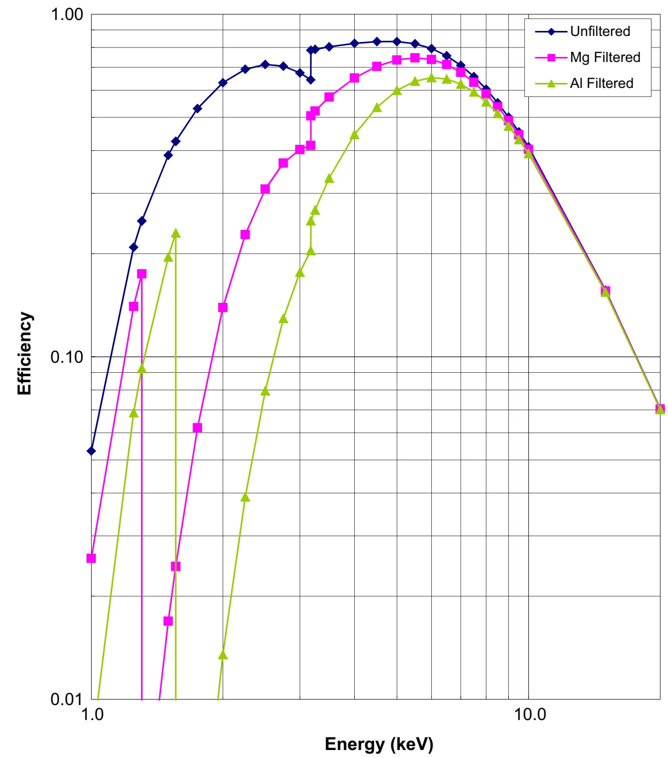

Fig. 1. Modeled detector efficiency versus energy for MESSENGER gas proportional counters (GPCs). Model results have been multiplied by 0.9 to take into account the non-uniform response of the GPCs, as discussed in the text. The effect of the Mg and Al filters at low energies is clearly seen. The break in the curve near 3.2 keV is the argon K-edge. The 25 μm-thick Be window attenuates the lower-energy X-rays in all three detectors.

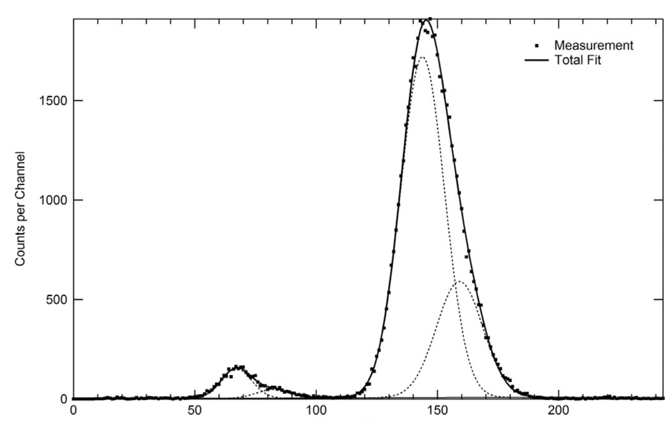

Fig. 2. Response of an unfiltered MESSENGER gas proportional counter to a radioactive ^{55}Fe source. The fit to the spectrum (solid line) is accomplished by including the K_α (5.90 keV) and K_β (6.49 keV) Mn lines in both the full-energy and escape peaks (dashed lines) plus a polynomial for the background. The fit for the full-energy K_α line gives a FWHM of 829 eV.