Icarus 209 (2010) 195–209

Contents lists available at ScienceDirect

Icarus

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

Identification and measurement of neutron-absorbing elements on Mercury's surface

David J. Lawrence [a,*], William C. Feldman [b], John O. Goldsten [a], Timothy J. McCoy [c], David T. Blewett [a], William V. Boynton [d], Larry G. Evans [e], Larry R. Nittler [f], Edgar A. Rhodes [a], Sean C. Solomon [f]

[a] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA
[b] Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719, USA
[c] National Museum of Natural History, Smithsonian Institution, Washington, DC 20560, USA
[d] University of Arizona, Lunar and Planetary laboratory, 1629 E. University Blvd., Tucson, AZ 85721, USA
[e] Computer Sciences Corporation, Lanham-Seabrook, MD 20706, USA
[f] Carnegie Institution of Washington, Washington, DC 20015, USA

ARTICLE INFO

Article history:
Received 23 October 2009
Revised 24 March 2010
Accepted 8 April 2010
Available online 13 April 2010

Keyword:
Mercury, surface

ABSTRACT

MESSENGER Neutron Spectrometer (NS) observations of cosmic-ray-generated thermal neutrons provide the first direct measurements of Mercury's surface elemental composition. Specifically, we show that Mercury's surface is enriched in neutron-absorbing elements and has a measured macroscopic neutron-absorption cross section of $45–81 \times 10^{-4}$ cm^2/g, a range similar to the neutron absorption of lunar basalts from Mare Crisium. The expected neutron-absorbing elements are Fe and Ti, with possible trace amounts of Gd and Sm. Fe and Ti, in particular, are important for understanding Mercury's formation and how its surface may have changed over time through magmatic processes. With neutron Doppler filtering – a neutron energy separation technique based on spacecraft velocity – we demonstrate that Mercury's surface composition cannot be matched by prior models, which have characteristically low abundances of Fe, Ti, Gd, and Sm. While neutron spectroscopy alone cannot separate the relative contributions of individual neutron-absorbing elements, these results provide strong new constraints on the nature of Mercury's surface materials. For example, if all the measured neutron absorption were due to the presence of an Fe–Ti oxide and that oxide were ilmenite, then Mercury's surface would have an ilmenite content of 7–18 wt.%. This result is in general agreement with the inference from color imaging and visible-near-infrared spectroscopy that Mercury's overall low reflectance is consistent with a surface composition that is enriched in Fe–Ti oxides. The incorporation of substantial Fe and Ti in oxides would imply that the oxygen fugacity of basalts on Mercury is at the upper range of oxygen fugacities inferred for basalts on the Moon.

1. Introduction

Despite many measurements from Earth and from the Mariner 10 spacecraft, there is little definitive information about the elemental composition of Mercury's surface (Goettel, 1988; Taylor and Scott, 2003). Specifically, there has been much debate about the Fe content of Mercury's surface materials (e.g., Sprague et al., 2007; Boynton et al., 2007). For example, 1-μm absorption bands resulting from Fe^{2+} in silicates are either absent or very weak in reflectance spectra of Mercury at visible to near-infrared wavelengths. Taken at face value, these observations have been interpreted to imply that the FeO concentration of both the crust and the mantle of Mercury must be very low. This conclusion contrasts with the fact that the high uncompressed density of Mercury indicates that some 60% of its mass must be iron metal. The surface Fe content may be an important discriminator for testing whether Mercury's high bulk metal fraction stemmed from aerodynamic drag in the early solar nebula (Weidenschilling, 1978), from preferential vaporization of silicates by an early hot solar nebula (Cameron, 1985; Fegley and Cameron, 1987), or from loss of the planet's original silicate crust and much of its mantle during a giant impact (Wetherill, 1988; Benz et al., 1988). Although we have only limited information on the abundance of FeO in Mercury's crust, information on the abundances of other key elements (e.g., Ca, Si, Mg, K, Ti) that are concentrated in planetary crusts during differentiation is even more restricted. Ti may be particularly informative, since, like FeO, it appears to be low in abundance in Mercury surface silicates (Warell and Blewett, 2004), but it couples with iron in a variety of Fe–Ti-oxides in crustal rocks on other bodies.

* Corresponding author. Address: Johns Hopkins University Applied Physics Laboratory, MP3-E169, 11100 Johns Hopkins Drive, Laurel, MD 20723, USA.
E-mail address: David.J.Lawrence@jhuapl.edu (D.J. Lawrence).

0019-1035/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2010.04.005

In 2008 and 2009, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft performed three flybys of Mercury (Solomon et al., 2008; Denevi et al., 2009) en route to insertion into orbit about the innermost planet in March 2011. Data from MESSENGER's Mercury Atmospheric and Surface Composition Spectrometer (MASCS) (McClintock et al., 2008) confirmed the absence of the 1-μm absorption feature expected for Fe^{2+} in silicates, in agreement with the earlier ground-based studies. Recent analyses of Mariner 10 (Denevi and Robinson, 2008) and MESSENGER Mercury Dual Imaging System (MDIS) color images (Denevi et al., 2009) and ground-based mid-infrared emission observations (Sprague et al., 2007, 2009) have led to the suggestion that Mercury's surface may have substantially more Fe and Ti in the form of oxides (e.g., ilmenite, $FeTiO_3$, or rutile, TiO_2) than was previously suspected. We note that all of these inferences are from spectral observations sensitive to mineralogical variations rather than elemental abundances. Moreover, spectral observations are affected by factors (e.g., space weathering, grain size variations) that are at best only partially understood but can cause variations unrelated to composition (e.g., Noble and Pieters, 2003).

We present in this paper the first analysis of neutron measurements from Mercury directly sensitive to the abundances of neutron-absorbing elements on Mercury's surface. We utilize observations by MESSENGER's Neutron Spectrometer (NS), which is part of the Gamma-Ray and Neutron Spectrometer (GRNS) instrument (Goldsten et al., 2007). Neutrons are produced on airless or nearly airless planetary bodies when galactic cosmic rays (GCRs) hit the surface, which occurs when any atmosphere is too thin to absorb the GCRs and the magnetic field is too low in magnitude to deflect them. Neutrons are produced by GCR-induced spallation reactions with energies in the range 1–100 MeV, down-scatter in energy through many orders of magnitude, and finally reach energies that are in thermal equilibrium with the planetary surface. A portion of these neutrons at all energies escapes to space and can be detected by a neutron sensor near the planet. The flux of thermal neutrons is highly sensitive to the presence of neutron-absorbing elements at the planet's surface. For solid planets with little to no hydrogen, the dominant neutron-absorbing elements are Fe and Ti. At sufficiently high abundances (tens of parts per million), Gd and Sm also cause measurable absorption of thermal neutrons because of their extremely large thermal neutron-absorption cross sections. The utility of thermal neutrons for measuring Fe, Ti, Gd, and Sm abundances has been demonstrated with the Lunar Prospector mission at the Moon (Feldman et al., 1998, 2000; Elphic et al., 1998, 2000, 2002). Although thermal neutrons cannot discriminate among different absorbing elements, they provide a highly sensitive measure of the presence and total abundance of all neutron-absorbing elements. Further, thermal neutrons provide depth-integrated measurements from up to a meter below the surface. Because neutron spectroscopy is not sensitive to the various mineralogical, space weathering, or grain-size effects inherent to spectral reflectance techniques, it provides a direct, complementary, and independent assessment of Mercury's surface elemental composition.

2. Neutron Spectrometer on the MESSENGER spacecraft

The MESSENGER NS (Fig. 1) consists of three scintillators that are each separately read out with photomultiplier tubes (PMTs) (Goldsten et al., 2007). The center block, a borated plastic (BP) scintillator, is sensitive to epithermal (0.4 eV to 500 keV) and fast neutrons (500 keV to few MeV), and the two planar lithium glass (LG) scintillators are sensitive to thermal (<0.4 eV) and epithermal neutrons. The NS is attached to the MESSENGER spacecraft on the side opposite the sunshade and is located close to one of three co-aligned spacecraft fuel tanks (Leary et al., 2007). The NS is positioned on the spacecraft so that the normal to the LG1 sensor points in the direction of the spacecraft +*x*-axis and the normal to the LG2 sensor points in the direction of the spacecraft $-x$-axis. These and other axes in the local spacecraft coordinate system are shown in Fig. 1.

The NS is designed to separately measure thermal and epithermal neutrons using the Doppler filter technique (Feldman and Drake, 1986). This technique takes advantage of the similarity in velocity between the spacecraft and thermal neutrons. An enhancement of thermal neutrons is measured when the spacecraft velocity vector is in line with the sensor normal vector; a relative decrease in thermal neutrons is measured when the spacecraft velocity vector is anti-parallel to the sensor normal. Finally, no Doppler effect occurs when the spacecraft velocity vector is perpendicular to the sensor normal vector.

3. Neutron Spectrometer data from three Mercury flybys

The MESSENGER spacecraft completed three flybys of Mercury on January 14, 2008 (M1), October 6, 2008 (M2), and September 29, 2009 (M3). Neutron data were collected during all three flybys, but different altitude-dependent spacecraft rotation maneuvers enabled measurements more sensitive to surface composition to be collected during M1 and M3 than during M2.

Pulse-height spectra from each LG sensor for M1 are shown in Fig. 2. Although not shown here, pulse-height data from M2 and M3 are similar. The peaks around channel 25 in each sensor are due to 4.78-MeV energy deposition from the $^{6}Li(n,\alpha)^{3}H$ reaction when neutrons are absorbed by the LG sensors. The averaged background is subtracted from the data near closest approach (CA) to give a net peak from the neutron detections (solid blue trace in Fig. 2). Except for excess counts at low-energy channels that are likely due to planetary gamma-rays, the net counts are well fit by a Gaussian function (dashed blue curve) that is similar in width to pre-launch calibration data (Goldsten et al., 2007). To avoid including any counts from the gamma-ray background in the summed neutron counts, we define the total measured neutron counts in each sensor as the total counts above channel 17. To account for neutrons not included in the low-channel Gaussian tail (i.e., since we are measuring counts above channel 17), we multiply the total counts by normalization factors that are dependent on the specific detector gain and energy resolution. More details of this data reduction process are given in Appendix A.

During each flyby, NS data were collected in 2-s time increments. These 2-s data were combined into 60-s time bins and the resulting time-series counting rates for M1, M2, and M3 are shown in Figs. 3–5. The error bars for the LG1 and LG2 counting rates are the 1-σ uncertainties from Poisson counting statistics, where σ is the estimated standard deviation (Bevington and Robinson, 1992) determined from the individual uncertainties of both the flyby and background data (see Appendix A). Figs. 3–5 also show spacecraft altitude and orientation information. The spacecraft orientation parameter most relevant to the NS is $\mathbf{V}\cdot\hat{x}/|\mathbf{V}|$, where $\mathbf{V}$ is the spacecraft vector velocity, and $\hat{x}$ is the spacecraft *x*-axis unit vector. $\mathbf{V}\cdot\hat{x}/|\mathbf{V}|$ gives a measure of the Doppler-filter effect: $\mathbf{V}\cdot\hat{x}/|\mathbf{V}| = +1$ indicates a thermal neutron enhancement for the LG1 sensor and $\mathbf{V}\cdot\hat{x}/|\mathbf{V}| = -1$ indicates a thermal neutron enhancement for the LG2 sensor. Figs. 3–5 show that as the spacecraft altitude decreases, the neutron counting rate in both LG sensors generally increases with peak counting rates near CA. The detailed time profile is substantially different between the two sensors. For M1 and M2, the LG1 profile generally shows a monotonic rise to CA with a slower fall after CA. For M3, the data stop at 21:48 UTC due to the fact that the MESSENGER spacecraft went