Earth and Planetary Science Letters 308 (2011) 107–114

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

# Constraints on Mercury's surface composition from MESSENGER neutron spectrometer data

M.A. Riner [a,*], P.G. Lucey [a], F.M. McCubbin [b], G.J. Taylor [a]

[a] Hawaii Institute for Geophysics and Planetology, University of Hawaii, Manoa, Honolulu, HI 96816, USA
[b] Institute of Meteoritics, Department of Earth & Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA

ARTICLE INFO

*Article history:*
Received 25 January 2011
Received in revised form 20 May 2011
Accepted 23 May 2011
Available online 24 June 2011

Editor: T. Spohn

*Keywords:*
Mercury
surface composition
MESSENGER neutron spectrometer

ABSTRACT

The composition of Mercury's surface is poorly known, but the MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) mission has provided a wealth of new data from three flybys. In particular, MESSENGER Neutron Spectrometer (NS) observations reveal a surface enriched in neutron absorbing elements, consistent with interpretations of color and albedo observations suggesting a surface composition enriched in Fe–Mg–Ti oxides. In this study, we have computed the neutron absorption cross sections for all of the available proposed surface compositions of Mercury and evaluated the plausibility of each surface composition based on the neutron absorption cross section observed by MESSENGER. For identified plausible compositions, the implications for the thermal and magmatic evolution of Mercury are discussed. The measured macroscopic neutron absorption cross section of Mercury is inconsistent with a crust formed from partial melting of plausible bulk mantle compositions, flotation in a magma ocean or adiabatic melting of upwelling cumulates during magma ocean overturn. However, the observed neutron absorption is consistent with model compositions of late-stage magma-ocean cumulates and some proposed compositions from spectral modeling and equilibrium modeling. This suggests that the enrichment of neutron absorbing elements may be indicative of the processes that acted to form Mercury's crust. The enrichment in neutron absorbing elements, in combination with spectral observations that constrain FeO in silicates (<2 wt.%), offers strong evidence of a magma ocean on Mercury since global scale melting appears to be required to concentrate the major neutron absorbing elements while minimizing Fe in silicate minerals. We also find that iron plays a secondary role in the neutron absorption of plausible surface compositions and its variations within different Fe–Mg–Ti oxide solid solution series does not cause any overlap among the various oxide series in neutron absorption cross section. High-Fe oxides are not required and more Mg-rich oxides may even be favored as the Ti-contents can sufficiently account for the observed neutron absorption.



## 1. Introduction

The MESSENGER mission has provided a wealth of new data that may shed light on Mercury's surface composition. In particular, much focus has been put upon determining the mineralogy of the mercurian surface from MESSENGER data so that models of surface composition can be constructed. The abundance of ferrous iron at the surface has been a primary focus, as ferrous iron abundance is a useful tracer of key formation and magmatic evolutionary processes. Furthermore, ferrous iron has a source/melt partition coefficient of approximately one, so mantle source region composition can be inferred from surface volcanic products (Robinson and Taylor, 2001; Taylor and Scott, 2004). However, the abundance of ferrous iron on Mercury has been the source of some debate. Earth-based, Mariner 10, and MESSENGER spectral observations have not detected a clear 1 μm absorption feature, indicating a low ferrous iron content in the silicate minerals (<2 wt.% FeO) that comprise the surface (Blewett et al., 1997, 2009; McClintock et al., 2008; McCord and Clark, 1979; Riner et al., 2010; Robinson and Lucey, 1997; Robinson et al., 2008; Vilas, 1988). In contrast, many authors have hypothesized the presence of abundant ferrous iron in non-silicate phases based on the observed high neutron absorption (Lawrence et al., 2010) and low albedo (Blewett et al., 2009; Denevi et al., 2009; Denevi and Robinson, 2008; Robinson et al., 2008) of the surface. Moreover, spectral and albedo evidences suggest a widespread abundant opaque component in Mercury's crust and a Fe–Mg–Ti-bearing oxide mineral is favored (Blewett et al., 2009; Denevi and Robinson, 2008; Denevi et al., 2009; Robinson and Lucey, 1997; Robinson et al., 2008). Denevi et al. (2009) estimate 15 vol.% opaque oxide mineral (possibly ilmenite) is needed in Mercury's widespread intermediate terrain to explain albedo and spectral variations between different crustal terrains on Mercury. A variety of opaque oxides with varying FeO contents are consistent with these observations (Riner et al., 2009, 2010) and more magnesian opaque oxide minerals are favored on equilibrium grounds (Riner et al., 2010;

* Corresponding author.
*E-mail addresses:* mariner@higp.hawaii.edu (M.A. Riner), mariner@higp.hawaii.edu (G.J. Taylor).

0012-821X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2011.05.042

Zolotov, 2011). The mineralogy of the opaque component is important because it influences the FeO content of the mercurian surface and suggested high oxide abundances imply an unusual crustal composition. Unfortunately, spectra of Mercury's surface are featureless throughout the visible to near infrared, making unique identification of minerals and estimation of FeO challenging. However insight into this problem can be made using the neutron absorption data collected by MESSENGER.

The neutron absorption of Mercury is sensitive to the elemental composition of the surface and thus provides information complementary to optical and infrared techniques about the surface composition. Galactic cosmic rays hit the surface of Mercury and induce spallation reactions that produce high-speed neutrons and interaction with the surface moderates these neutrons to thermal equilibrium. The externally measured flux of neutrons in thermal equilibrium with the surface is sensitive to the surface composition because important elements can absorb thermal neutrons (e.g. Feldman et al., 2000). Mercury's measured neutron absorption cross section can be directly compared with estimates of Mercury's surface composition. Lawrence et al. (2010) reported that the observed neutron absorption cross section is consistent with low-FeO silicates and 7–18 wt.% ilmenite but is not consistent with partial melting of three proposed bulk mantle compositions from Taylor and Scott (2004): enstatite chondrite, bencubbinite chondrite (CB), and a model composition of Mercury (Morgan and Anders, 1980).

A wide variety of surface compositions have been proposed for Mercury, many of which are derived using very different techniques and constraints (see Supplemental Material, Tables S3–S6, for complete details). Therefore in the present study we have explored the neutron absorption of additional compositions, including previously proposed Mercury mantle compositions (Taylor and Scott, 2004), compositions derived from detailed spectral analysis of near- and mid-IR spectra (Sprague et al., 2009; Vernazza et al., 2011; Warell et al., 2010), compositions from equilibrium petrologic modeling (see Section 3.3 for details) (Riner et al., 2010), and compositions of three different oxide solid solution series [this study]. Using the computed neutron absorption cross-section values, we evaluate the plausibility of each surface composition based on the neutron absorption cross section observed from MESSENGER. For all plausible compositions identified, the implications for the thermal and magmatic evolution of Mercury are discussed.

## 2. Computing neutron cross sections for candidate mercury compositions

A material's macroscopic absorption cross section (symbolized as $\Sigma_a$) characterizes the material's ability to absorb thermal neutrons and is the weighted sum of all the constituent elements ability to absorb neutrons:

$$\Sigma_a = \sum_i \frac{f_i \sigma_i N_A}{A_i} \qquad (1)$$

where $\sigma_i$ is the thermal neutron absorption cross section (in barns, b) of constituent element i, $f_i$ is the mass fraction, $N_A$ is Avogadro's number, and $A_i$ is the atomic mass of constituent element i (Elphic et al., 2000). Although the relatively abundant absorbing elements Fe and Ti, along with the trace but highly absorbing elements Sm and Gd drive the thermal neutron flux of a planetary body (e.g. the Moon), the other (moderate to low absorbing) elements also contribute to the total neutron absorption due, in part, to their high abundance. For example, Mercury's intermediate terrain has a neutron absorption cross section of $45\text{–}81\times10^{-4}\,cm^2/g$, comparable to Luna 16 and 20 sites on the Moon (Lawrence et al., 2010). A surface of pure plagioclase feldspar would have a cross section of $26\text{–}29\times10^{-4}\,cm^2/g$ (depending on sodium content), ~25% to 50% of the absorption exhibited by Mercury with no Fe, Ti, Sm, or Gd present. On the Moon, elements other than Fe, Ti, Sm and Gd can make up more than 50% of the total neutron absorption, however these regions tend to have lower overall absorption (Fig. 1).

Table 1 lists the thermal neutron absorption cross-section and $\sigma_i N_A/A_i$ (equivalent to $\Sigma_a$ with $f=1$) of the key major and minor elements. For convenience, we have tabulated $\sigma_i N_A/A_i$ for some elements expressed as oxides (in the valence state expected on Mercury (Table 2)). Additionally we have calculated $\sigma_i N_A/A_i$ for the silicate and oxide minerals considered in the present study (Table 2).

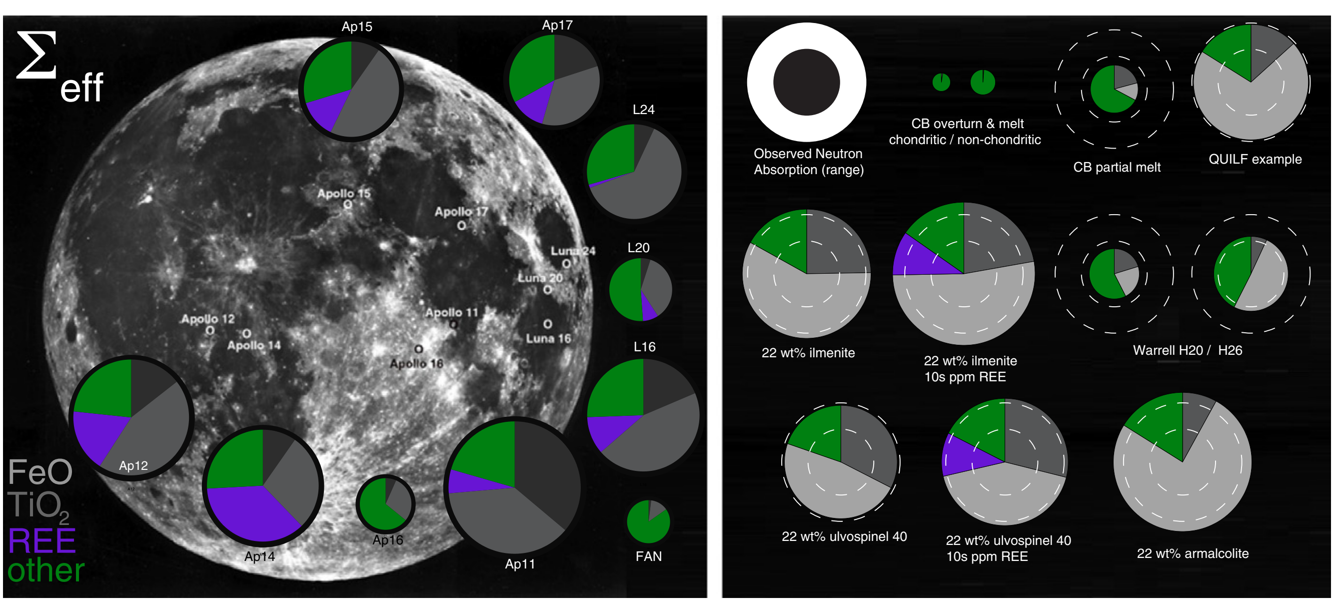


**Fig. 1.** Total neutron absorption broken down by Fe, Ti, REE (Sm and Gd) and all other elements for (left) lunar sample sites (Lawrence et al., 2010) and (right) modeled Mercury crustal compositions [this study]. FAN stands for Ferroan Anorthosite, we use the composition defined by Lawrence et al., 2010. The diameter of each pie chart is proportional to the total neutron absorption. The macroscopic neutron absorption cross section of Mercury's surface reported by Lawrence et al. (2010) is shown by the white ring and superimposed on the pie charts as dotted circles (plausible values lie between the two). Note the observed macroscopic neutron absorption cross section of Mercury falls between those for Luna 20 and Luna 16 sample sites (Lawrence et al., 2010). Values for each pie chart can be found in the online Supplementary Material (Table S1).