

CHLORINE ON THE SURFACE OF MERCURY: IMPLICATIONS FOR MERCURY'S SURFACE EVOLUTION. Larry G. Evans¹, Patrick N. Peplowski², Denton S. Ebel³, David J. Lawrence², Timothy J. McCoy⁴, Larry R. Nittler⁵, Richard D. Starr⁶, Shoshana Z. Weider⁵, and Sean C. Solomon^{5,7}, ¹Computer Science Corporation, 2900 Harkins Rd., Lanham, MD 20706 USA (larry.g.evans@nasa.gov); ²Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA; ³Dept. of Earth and Planetary Science, American Museum of Natural History, New York, NY 10024, USA; ⁴National Museum of Natural History, Smithsonian Institution, Washington DC 20013, USA; ⁵Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA; ⁶Physics Department, The Catholic University of America, Washington DC, 20064; ⁷Lahmont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA.

Introduction: The nature and origin of volatile elements on the surface of Mercury have long been outstanding questions [1]. Many of the formation mechanisms proposed for Mercury predict that the present-day surface should be volatile depleted. The MESSENGER spacecraft carries an extensive payload of scientific instruments designed, in part, to examine volatiles on the surface. Orbital measurements of the surface composition made by the X-Ray Spectrometer (XRS) and Gamma-Ray Spectrometer (GRS) have led to the discovery of relatively high surface abundances of the volatile elements S, K, and Na [2–4]. Here we report on the further analysis of GRS measurements to establish the bulk abundance of the volatile element chlorine on the surface of Mercury and provide some information on its spatial distribution.

Gamma-Ray Measurements: Previous analyses of MESSENGER gamma-ray measurements have yielded the abundances of K, Th, U, Na, Al, S, Ca, and Fe [3–6]. There were also early indications of Cl gamma rays in the spectra. Cl has a large cross-section for thermal neutron capture and a large number of strong gamma rays, with the most prominent at 1951 keV, 1959 keV, and 6111 keV. The 6111-keV line has three associated peaks: the full-energy peak and two escape peaks (Fig. 1A). There is another weaker Cl peak at 6624 keV (consisting of two peaks at 6620 and 6627 keV) that interferes with the full-energy and single-escape peaks of the 6111-keV gamma ray. Additionally, the 6111-keV peak overlaps with the strong 6129-keV O gamma ray (Fig. 1A). The analysis of the 6111-keV peak, therefore, requires a correction for the interferences and the escape peak detection efficiency. To give a first estimate, the relative intensities of the oxygen peak at 6129 keV and a titanium peak at 6756 keV were used to scale the contributions from the higher-energy Cl peaks. The low-energy gamma rays were difficult to characterize from the normal low-altitude spectrum (< 2000 km), which showed no resolvable peaks. Use of low-altitude cutoffs of 1500 km and 1000 km improved the signal-to-background of the spectra for these gamma rays (Fig. 1B). Since the 1000 km cutoff gave the best count rate for the two low-energy peaks (summed as a single peak at 1955 keV),

this cutoff altitude was used for the analysis of all four peaks. The analysis was carried out in a manner similar to that for the other neutron capture peaks (i.e., normalized to the Si capture peak [4]). The results are given in Table 1.

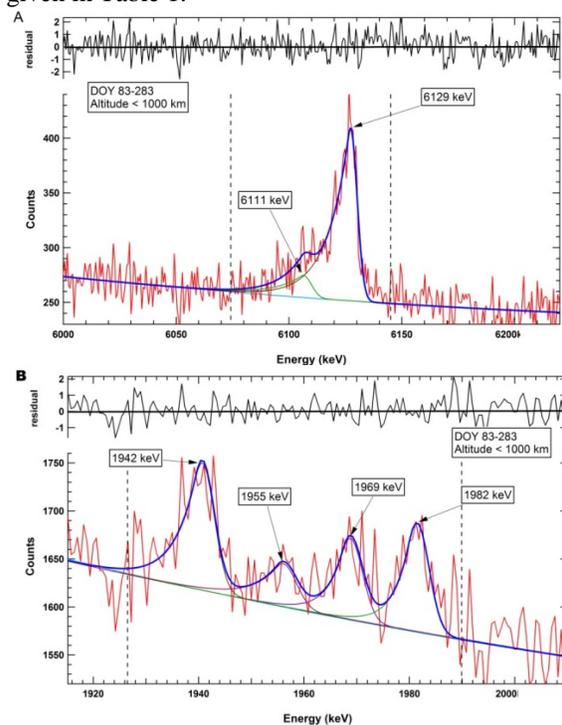


Figure 1. Fits to the high-energy and low-energy Cl peaks at (A) 6111 keV and (B) 1955 keV (the sum of the 1951 and 1959 keV peaks). DOY is day of year (2011).

Spatial Variability: Since Cl and K are both incompatible volatile elements, their abundances may be related, and the spatial dependence for K on Mercury [5] may correlate with a similar latitudinal variation for Cl. The low count rates for the Cl gamma rays do not permit detailed mapping, but they do allow analysis of two broad latitude bands, 0°–60°N and 70°–90°N, as was done for Na GRS measurements [7]. Analysis of the spectra from these two bands shows a significant difference in Cl abundances (Table 1).

In particular, the abundance of Cl increases with latitude on Mercury in a manner similar to K and Na

Table 1. Cl Results.

Spatial coverage	Cl/Si	Cl wt%*
Northern hemisphere	0.0057±0.001	0.14±0.03
0°–60° N	0.0049±0.0007	0.12±0.02
70°–90° N	0.015±0.003	0.36±0.08

*For a Si abundance of 24.6 wt%.

[5, 7]. The presence of higher K and Na abundances at high northern latitudes has been attributed either to thermal mobilization of these moderately volatile lithophile elements or intrinsic geochemical differences related to plains volcanism [5,7]. Similar processes may have led to higher Cl abundances in Mercury's north polar region.

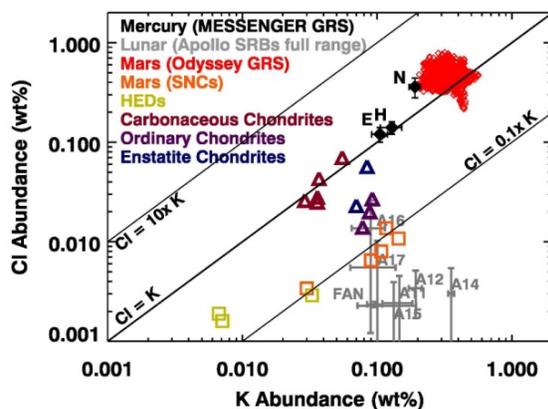


Figure 2. Relation between K and Cl for Mercury; H, E, and N denote the northern hemisphere, equatorial region, and northern plains, respectively. Data for other solar system objects [8–10] are shown for comparison.

Interpretation: In addition to reinforcing the newly established evidence that Mercury's surface is not volatile depleted, the discovery of Cl on the surface of Mercury addresses many other outstanding questions. These include the following:

1. Pre-MESSENGER theories for the formation of Mercury [e.g., 11] generally invoked high-temperature processes to account for the planet's large Fe core. These mechanisms would have depleted the planet in volatile elements such as S, K, Na, and Cl. The overwhelming evidence from MESSENGER that these elements are not depleted on Mercury's surface [2–5] conclusively rules out these volatile-depleting formation mechanisms as they are currently understood.

2. Chlorine has been proposed to be an important magmatic volatile on Mercury [12]. The observation of higher Cl abundances in association with northern regions, which include a large expanse of smooth volcanic plains units [13], supports this hypothesis, although the Cl abundance pattern may instead be the

result of thermal redistribution to cooler regions of the surface [e.g., 5, 7].

3. EH enstatite chondrites, which have been suggested as a possible meteoritic analog for Mercury or its precursory material [2, 16], are known to have elevated Cl abundances. Condensation calculations predict a direct connection between K and Cl in highly reduced systems [14]. Our observation of Cl on Mercury's surface supports the idea that EH chondrites or their partial melts are candidate analogs for Mercury surface material.

4. K and Cl abundances are expected to be related as both are incompatible, moderately volatile, lithophile elements. The apparent correlation for these two elements, which is similar to that observed in the SNCs, HEDs, and carbonaceous chondrites (Fig. 2) supports this hypothesis. The observed enhancement in the north polar region could be due to thermal redistribution [5,7] of these elements to cooler polar latitude or concentration of these elements in melts exposed at the surface within the northern volcanic plains unit.

5. Chlorine may be a major absorber of thermal neutrons on Mercury's surface. This inference has implications for the mapping of thermal neutrons by the GRS shield and the Neutron Spectrometer (NS). Measurements of thermal neutrons made by the NS during MESSENGER's flybys of Mercury [15] were consistent with a high ilmenite (a Ti-Fe oxide) content of 7–18 wt%. Subsequent measurements from orbit by both the GRS and XRS show that the Fe and Ti abundances are much lower than were inferred from the neutron measurements. Chlorine, with its large thermal neutron capture cross-section (~ 200 times that of Si, ~10 times that of Fe), could account for some of the measured thermal neutron absorption.

References: [1] Solomon, S.C. et al. (2007) *Space Sci. Rev.* 131, 3–39. [2] Nittler, L.R. et al. (2011) *Science*, 333, 1847–1850. [3] Peplowski, P.N. et al. (2011) *Science*, 333, 1850–1852. [4] Evans, L.G. et al. (2012) *JGR*, 117, E00L07. [5] Peplowski, P.N. et al. (2012) *JGR*, 117, E00L04. [6] Peplowski, P.N. et al. (2012) *JGR*, 117, E00L10. [7] Peplowski, P.N. et al., (2014) *Icarus*, 228, 86–95. [8] Boynton, W.V. et al. (2007) *JGR*, 112, E12S99. [9] Lodders, K. and Fegley Jr., B. (1998) *The Planetary Scientist's Companion*, Oxford. [10] Haskin, L. and Warren, P. (1991) in *Lunar Sourcebook*, Cambridge. [11] Fegley Jr., B. and Cameron, A.G.W. (1987) *Earth Planet. Sci. Lett.*, 82, 207–222. [12] Zolotov, M.Yu. (2011) *Icarus*, 212, 24–41. [13] Denevi, B.W. et al. (2013) *JGR Planets*, 118, 891–907. [14] Ebel, D.S. and Sack, R.O. (2013) *Contrib. Mineral. Petrol.* 166, 923–934. [15] Lawrence, D.J. et al. (2010) *Icarus*, 209, 195–209. [16] McCoy, T.J. et al. (1999) *Meteorit. Planet. Sci.*, 34, 735–746.