CRITERIA FOR IDENTIFYING MERCURIAN METEORITES.

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Introduction: When did Mercury's core form? What is the age of Mercury's crust? What is the composition of Mercury's mantle? The answers to these important questions about Mercury probably await the analysis of a sample from that planet. However, an *in situ* sample analysis mission (much less a sample return mission) does not seem imminent. For the time being, only natural processes are likely to transport rocks from Mercury to Earth. Yet natural processes deliver rocks from asteroids and the Moon and Mars to Earth much more frequently than from Mercury to Earth [1]. Given that exogeneous rocks are derived from many parent bodies, how can we associate an exogeneous rock with Mercury? In short, how can we identify mercurian meteorites?

Meteorites have been recognized to derive from Mars or the Moon on the basis of the resemblance of their trace element abundance ratios or isotopic compositions to planetary abundances measured *in situ* or in returned samples [*e.g.,* 2-3] under the assumption that no two parent bodies have the same trace element abundance ratios or isotopic abundances. It is not currently possible to recognize mercurian meteorites according to these criteria, as the trace element composition or isotopic abundance of mercurian rocks is unknown. (Of course, it may be possible to determine the trace element composition or the isotopic composition of Mercury from the analysis of mercurian meteorites, but to then use these criteria to identify mercurian meteorites is circular.)

However, before despairing of whether it is possible to identify mercurian meteorites at all, it is important to note that SNC meteorites were identified as deriving from Mars [4] *before* the recognition that these meteorites had the same trace gas fingerprint as Mars [3]. How was the identification of these meteorites accomplished? Wood and Ashwal [4] recognized that planetary meteorites, being derived from planetary bodies, share certain characteristics of those parent bodies: the lithology and formation age of a planetary meteorite should fit into the geologic history of its parent planet; the chemistry of a meteorite should be similar to the chemistry of surficial lithologies (or fractionates of those surficial lithologies, if the compositions of those lithologies represent melt compositions) and consistent with inferred mantle compostions on its parent planet (as determined by remote sensing techniques); and the remanent magnetism (if any) and space weathering effects in a meteorite should be consistent with the geophysical history and space environment of its parent planet.

In short, although it may not be possible to *recognize* mercurian meteorites (taking "recognize" to mean "to know again", since the distinctive trace element abundance ratio and isotopic composition that constitutes the fingerprint of Mercury is unknown in the first place), it is probably possible to *identify* mercurian meteorites (taking "identify" to mean "to associate closely with") by means of their consistency with the known characteristics of Mercury: its geological history, its surface composition, its geophysical state, and its space environment. In 1992, Love and Keil [5] used the characteristics of Mercury as they were then known to outline a number of criteria (with which we largely still agree) for identifying mercurian meteorites such as composition, crystallization ages, magnetic remanence, *etc*. Several abstracts by Irving [6-7], which propose that certain unusual achondrites are derived from Mercury, suggest additional petrographic and mineralogical criteria for identifying mercurian meteorites. (A valuable webpage [8] collects references such as [5-7] pertaining to criteria for identifying mercurian meteorites.)

However, recent developments may require some revision of these older criteria [5-6]. In March 2011, the NASA MESSENGER spacecraft [9] entered orbit around Mercury. Its ongoing observations of Mercury have substantially improved our knowledge of the characteristics of that planet. Critically, MESSENGER X-ray and gamma-ray spectrometer measurements have determined the major element chemistry of Mercury's surface [10-13], which was previously unknown. In 2013, Irving [7] proposed that an unusual achondrite somewhat resembling the composition of Mercury's surface was a mercurian meteorite. Due to our increasing knowledge of Mercury as a result of the MESSENGER mission, as well as the recent interest in a putative mercurian meteorite [7], it is worthwhile to revisit the problem of identifying mercurian meteorites. In this abstract, we develop criteria for identifying mercurian meteorites based on the characteristics of Mercury as they are now understood.

Some criteria for identifying mercurian meteorites:

Likely depth of origin. From what depth are mercurian meteorites most likely derived? Warren [14] observed that lunar meteorites are systematically derived from shallower depths than martian meteorites. His interpretation of this observation is the lunar subsurface is lithified at a shallower depth than the martian subsurface, perhaps due to weathering of the martian surface by wind or water. Mercury is likely more similar to the Moon than Mars in this regard. Therefore, some mercurian meteorites may be derived from shallow depths (several meters below Mercury's surface). This is fortuitous, as two unique characteristics of Mercury (its high surface temperatures and its intense space environment) mainly affect those rocks nearest Mercury's surface.

Likely location of origin. From where on Mercury are mercurian meteorites most likely derived? Dynamically, not all locations on Mercury are equally probable meteorite source regions. For example, a meteorite ejected from Mercury's orbital apex at perihelion (*i.e.*, spalled from the surface by the formation of a source crater ~30° away from one of Mercury's cold poles, assuming an ejection angle of ~60°) requires an ejection velocity of ~8 km/s to reach Earth. Conversely, a meteorite ejected from Mercury's orbital apex at aphelion (*i.e.*, spalled from the surface by the formation of a source crater ~30° away from one of Mercury's hot poles, assuming an ejection angle of ~60°) requires an ejection velocity of ~12.5 km/s to reach Earth. Assuming that a lower required ejection velocity translates to a higher probability of reaching Earth, annuli centered at about 30° around Mercury's cold poles (which have the lowest required ejection velocities) are the most probable mercurian meteorite source regions. (Though these annuli surround the "cold" poles, the surface temperatures here can nevertheless exceed 300 °C, temperatures sufficiently high to drive diffusion of alkali elements such as Na and K across mercurian minerals [13] over Ga timescales.)

Lithology and age. Two major geologic units comprise Mercury's surface [15]: relatively young, volcanic [16], high-reflectance *smooth plains* and somewhat older (*i.e*., more heavily cratered) low-reflectance *intercrater plains*. The nature of intercrater plains is ambiguous. Some low-reflectance plains are apparently composed of impact melt from large basin-forming impacts [15]. However, intercrater plains units that are not associated with large basins are by no means unambiguously volcanic. The crater size-frequency distributions of intercrater plains units are consistent with a ~4 Ga age [17]. Mercurian meteorites are most likely to be derived from the intercrater plains, as only about one-quarter of Mercury's surface (~27%) is covered with smooth plains [18]. Moreover, since most smooth plains units occur at relatively high latitudes (an expanse of volcanic plains centered on Mercury's north pole constitutes ~6% of Mercury's surface), and (according to the arguments above) mercurian meteorites are more likely to be derived from low latitudes, it is doubly likely that mercurian meteorites come from the intercrater plains.

Composition and mineralogy. Earth-based spectral observations of Mercury at UV-vis and microwave wavelengths [19-20] demonstrate that Mercury's crust is poor in FeO. This spectral observation is ambiguous, consistent with two conflicting interpretations: either (1) Mercury's crust has *no* FeO-bearing *mafic* minerals or (2) the *mafic minerals* comprising Mercury's crust *bear no FeO*. Spectral observations of Mercury at X-ray and gamma ray wavelengths [10-13] by the MESSENGER Mercury orbiter demonstrate that Mercury's crust is poor in Ca and Al and rich in Mg and S. This rules out interpretation (1) above—Mercury's crust does not resemble in composition the feldspathic crust of the Moon—and supports interpretation 2—Mercury's crust resembles in composition the reduced enstatite achondrite meteorites. Normative calculations based on X-ray spectrometer derived chemistry [21] indicate that smooth plains consist mainly of albite and magnesian orthopyroxene, whereas the intercrater plains comprise labradorite, magnesian orthopyroxene, and several wt. % sulfides.

Complementarity of mercurian meteorites and *in situ* sample analysis or sample return missions: According to the arguments above, the most probable mercurian meteorite is a ~4 Gya breccia comprising mainly norite clasts (*i.e.* clasts with Na-bearing labradorite feldspar and orthopyroxene) with minor (endogenous) calcium and iron sulfide [22] derived from near the surface of an intercrater plains unit relatively near Mercury's equator (and therefore having a mild "sunburn" due to high surface temperatures, perhaps reflected by gradients in the concentration of volatile alkali elements or even exsolution lamellae in sulfides). By contrast, the most probable landing site for a Mercury lander is in the young volcanic plains near Mercury's north pole, where surface temperatures are survivably low and surficial ice deposits provide an important science target. (For example, the BepiColombo Mercury Surface Element, a now-cancelled lander, was intended to land at latitude 85 °N.) Such a lander would collect or analyze a very different type of mercurian rock: ~3.8 Gya volcanic flow closer to an "anorthositic norite" [22] in mineralogy with very Na-rich albite feldspar, minor orthopyroxene, and clinopyroxene), fewer sulfides, and little evidence of alteration by surface temperatures. Therefore, the study of mercurian meteorites (once found using the criteria outlined here) promises to provide information that will not be superceded by, but will rather be complementary to, future sample return or analysis missions.

Acknowledgments: We thank Ken Ramsley, who developed the dynamical ideas in this abstract.

References: [1] Gladman, B. and J. Coffey (2009) *Meteorit. Planet. Sci., 44*. [2] Bogard, D. D. and P. Johnson (1983) *Science, 221*. [3] Mayeda et al. (1983) *GRL, 10*. [4] Wood, C. A. and L. D. Ashwal (1981) *Proc. Lunar Planet. Sci., 12*. [5] Love, S. G. and K. Keil (1995) *Meteoritics, 30*. [6] Irving, A. J. and S. M. Kuehner (2007) *Workshop on Chronology of Meteorites,* abstract 4050. [7] Irving, A. J. et al. (2013) *LPSC*, abstract 2164. [8] Weir, D. http://www.meteoritestudies.com/protected_MERCURY.HTM [9] Solomon, S. C. et al. (2007) *Space Sci. Rev., 131*. [10] Nittler L. R. et al. (2011) *Science, 333*. [11] Weider S. Z. et al. (2012) *JGR, 117*. [12] Evans L. G. et al. (2012) *JGR, 117*. [13] Peplowski P. N. et al. (2012) *JGR, 117*. [14] Warren, P. H. (1994) *Icarus, 111*. [15] Denevi B. W. et al. (2009) *Science, 324*. [16] Head, J. W. et al. (2011) *Science, 333*. [17] Marchi, S. et al. (2013) *Nature, 499*. [18] Denevi, B. W. et al. (2013) *JGR, 118*. [19] Vilas, F. (1989) in *Mercury*. [20] Jeanloz, R. et al. (1995) *Science, 268*. [21] Stockstill-Cahill, K. R. et al. (2012), *JGR, 117*. [22] Vaughan, J. W. et al. (2013) *LPSC*, abstract 2013.