MERCURIAN METEORITES: PROPERTIES AND PROBABILITIES S. G. Love and K. Keil, Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822

With the recent realization that some meteorites may come from Mars [1] and the Moon [2], it is worthwhile to consider whether meteorites from Mercury could exist in our collections and, if so, whether they could be recognized [3]. We know very little about Mercury, a state of affairs which both increases the scientific value of mercurian meteorites and aggravates the problem of identifying them. As the innermost planet, Mercury contains unique information about limits on the formation of planets. Here we review evidence supporting the possibility of rocks being delivered from Mercury to Earth, and suggest criteria which could help identify a mercurian meteorite. Mercurian rocks are probably differentiated igneous rocks, or breccias or impact melt rocks derived therefrom. They are probably low in volatiles and moderately enriched in Al, Ti, and Ca oxides. Mercurian surface rocks contain no more than 5% FeO and may contain plagioclase. A significant fraction may be volcanic. Most pristine mercurian rocks should have solidification ages of ~ 3.7 to ~ 4.4 Ga, but younger impact-remelted materials are possible. The unique solar-to-galactic cosmic ray damage track ratio expected in materials exposed near the Sun may be useful in identifying a rock from Mercury. Mercury's magnetic field stands off the solar wind, so solar wind implants in mercurian regolith breccias may be scarce or fractionated compared to lunar ones. Mercurian regolith breccias should contain more agglutinates, impact vapor deposits, and exogenic chondritic materials than analogous lunar breccias. No known meteorite matches these criteria, but we should recall the lesson of the unforeseen lunar and martian meteorites, and be prepared to accept Mercury as a potential meteorite parent body. A misclassified mercurian meteorite would most likely be found among differentiated, low-FeO objects such as the aubrites or the anorthositic lunar meteorites.

DELIVERY OF MERCURIAN ROCKS The existence of meteorites from Mars and the Moon suggests that rocks can be launched from Mercury by impacts, although the relative frequency and efficiency of such events are not known. Orbital evolution of mercurian materials to Earth-crossing orbits appears possible, but its efficiency is less than 1% of that computed for Mars: no more than 10^{-4} of the mass leaving Mercury reaches Earth [4]. Scaling to the number of known martian meteorites, we estimate the number of mercurian rocks in current meteorite collections to be zero (>90% chance) or one (<10% chance). These odds are low, but they are not zero, and as the collections grow in the future the probability will increase accordingly.

CHARACTERISTICS OF MERCURIAN ROCKS The current availability of samples allows lunar, martian, and asteroidal meteorites to be identified by their *isotopic composition* [5], but to identify meteorites from Mercury we must, at least initially, rely on other discriminators. The *major element composition* of Mercury's rocks is not well known, but an uncertain "preferred model" [6] suggests a moderate enrichment of Al_2O_3, CaO, and TiO_2, with depletions in FeO, FeS, the alkali elements, and water. The last constraint is weakened by the apparent presence of ice near Mercury's poles [7]: rare polar rocks could contain abundant water. Mercury is highly differentiated [6]; mercurian meteorites must come from the metal-poor crust and mantle. An FeO absorption feature near 0.9 μm (subject to strong telluric interference) has been intermittently detected in Mercury's reflectance spectrum, suggesting that Mercury's surface contains no more than 5% FeO [8]. Mid-infrared spectroscopic evidence for plagioclase on Mercury has been presented [9]. Geomorphological [10] and spectral [9] features consistent with basaltic volcanism have been detected as well.

The *solidification ages of pristine rocks* can constrain their origin. Crater counts [10] indicate that Mercury's surface solidified more than 4.0 Ga ago. Flood lavas analogous to the lunar maria may exist on Mercury, but their emplacement would have occurred before or during the mid-Calorian (~ 3.7 Ga) period, after which impacts appear to have been the primary resurfacing process. Thus, most pristine mercurian rocks (excluding impact melts) should have solidification ages greater than ~ 3.7 Ga. The planet may have had a primordial global magma ocean with a lifetime of ~ 100 Ma, as is widely believed in the case of the Moon [11]; pristine mercurian rocks should thus not predate the oldest lunar rocks, which have measured ages near 4.44 Ga [12].

Mercury's magnetic field stands off the solar wind under most conditions [13], so we expect mercurian regolith breccias to be relatively low in *implanted solar wind gases*. A small flux of solar wind particles may "leak" through the magnetic field, but this process would be inefficient [14] and might fractionate solar wind ions by charge-to-mass ratio, producing a unique chemical abundance pattern. *Cosmic ray effects* may help identify surface-exposed rocks from Mercury. The solar (SCR) and galactic (GCR) cosmic ray fluxes vary systematically with distance from the sun [15]. A meteorite exhibiting a sufficiently large ratio of SCR to GCR track damage was probably exposed near the sun, and could be tentatively identified as mercurian. The micrometeorite flux on Mercury is ≈ 5 times higher than on the Moon, so small-scale impact effects (*exogenic chondritic material, microcraters, agglutinates, and impact vapor deposits*) should be more common on Mercury than on the Moon [14].

Although information on Mercury's magnetic history, thermal environment, and radar properties is available, it is of questionable utility in identifying mercurian rocks.

MERCURIAN METEORITES IN THE COLLECTIONS? All *chondrites* (including the low-FeO EH and EL enstatite chondrites) are from primitive, undifferentiated parent bodies and thus could not have come from Mercury. *Iron meteorites* represent differentiated core material, and there is no evidence for an impact on Mercury recent enough to supply meteorites in current collections and large enough to excavate material from the planet's core. *Stony-iron meteorites*, which also contain core materials, are unlikely to have come from Mercury for the same reason.

If mercurian meteorites exist in our collections, they must be among the achondrites. The *acapulcoites* and *lodranites* are not highly differentiated rocks [16] and their bulk FeO contents are inconsistent with spectral observations of Mercury. This is also true for the *winonaites*, another group of primitive achondrites [17]. Two rocks of extremely low FeO content, *Ilafegh 009* and *Happy Canyon*, are probably impact melts from the EL parent body [18]. The ancient I-Xe ages of 1.6 and 1.4 Ma before Bjurböle for, respectively, Ilafegh 009 and Happy Canyon [18], are more consistent with an asteroidal than a mercurian origin.

A mercurian origin for the *howardites*, *eucrites*, and *diogenites* (HED) can be ruled out on the basis of their 16 to 19 % FeO contents [19], abundant solar wind gas, lack of agglutinates [20], and ages of 4.5 Ga [19] which makes them older than the likely date of formation of Mercury's crust. Similarly, the *ureilites* have 9 to 25 % FeO [19] and no agglutinates, and at least one brecciated ureilite is rich in solar-wind implants [21]. Ureilites typically contain 3 to 6 % metallic iron [19] with a primitive trace element pattern [21], evidence of incomplete differentiation and a strong argument against a mercurian origin. The *angrites* show crystallization ages near 4.55 Ga [22], and their FeO contents are near 8% [23], both inconsistent with mercurian origin. *Brachina* does not have a reliably determined crystallization age, but its 24% FeO content [24] is outside the mercurian range.

The *aubrites* (enstatite achondrites) are highly reduced enstatite pyroxenites, very low (< 0.1%) in FeO [25]. There are ~ 30 aubrites in our collections, several hundred times too many for them to have come from Mercury (although the stochastic nature of planetary launch and delivery mechanisms weakens this argument). All aubrites (except Shallowater; see below) appear to come from the same parent body [25]; thus, the lack of agglutinates and abundant solar wind implants in aubrite regolith breccias [26] argues against a mercurian origin for these objects. Aubrites contain primitive metallic Fe,Ni with roughly chondritic trace element abundances [27], attesting to incomplete core formation and thus inconsistent with an origin on Mercury. The *Shallowater* aubrite is thought to come from a second aubrite parent body [28]. Although this rock has igneous texture and extremely low FeO content, it contains appreciable amounts of metallic Fe,Ni and FeS [28], inconsistent with a mercurian origin. Also, Shallowater has a very ancient I-Xe closure age [18], and is thus too old to be from Mercury.

The *SNC meteorites* are probably from Mars [1]. Their crystallization ages are near 1.3 Ga [19] and their FeO contents are 16 to 27 % [19, 29], both outside the likely mercurian range. Two shergottites have been isotopically linked to the martian atmosphere [30]. The ages and FeO abundances of *lunar meteorites* may overlap with the mercurian range, but comparison with Apollo samples permits confident identification of lunar meteorites [2, 31]. Lunar regolith breccias are rich in solar wind implanted gas with a distinctly lunar chemical abundance pattern [32]. An anorthositic lunar meteorite containing no surface-exposed or mare-derived materials might, however, be difficult to distinguish from a mercurian one based on present knowledge.

REFERENCES [1] Mittlefehldt D. W. (1994) *Meteoritics* **29**, 214. [2] Hill D. H. *et al.* (1991) *Nature* **352** 614. [3] Warren P. H. *et al.* (1983a) *Lunar Planet. Sci. XIV*, 41. [4] Wetherill G. W. (1984) *Meteoritics* **19**, 1. [5] Sears D. W. G. and Todd R. T. (1988) In *Meteorites and the Early Solar System* (eds. J. F. Kerridge and M. S. Matthews), 3. [6] Goettel K. A. (1988) In *Mercury* (eds. F. Vilas, C. R. Chapman, and M. S. Matthews), 613. [7] Butler B. J. *et al.* (1993) *J. Geophys. Res.* **98** 15,003. [8] Vilas F. (1988) In *Mercury* (eds. F. Vilas, C. R. Chapman, and M. S. Matthews), 59. [9] Sprague A. L. *et al.* (1994) *Icarus* **109**, 156. [10] Spudis P. D. and Guest J. E. (1988) In *Mercury* (eds. F. Vilas, C. R. Chapman, and M. S. Matthews), 118. [11] Warren P. H. (1985) *Ann. Rev. Earth Planet. Sci.* **13**, 210. [12] Taylor G. J. *et al.* (1991) In *Lunar Sourcebook: A User's Guide to the Moon* (eds. G. Heiken, D. Vaniman, and B. M. French), 183. [13] Russell C. T. *et al.* (1988) In *Mercury* (eds. F. Vilas, C. R. Chapman, and M. S. Matthews), 514. [14] Cintala M. J. (1992) *J. Geophys. Res.* **97**, 947. [15] Nishiizumi K. *et al.* (1991) *Earth Planet. Sci. Lett.* **104**, 315. [16] McCoy T. J., *et al.* (1995) *Geochim. Cosmochim. Acta* (in preparation). [17] Prinz M. *et al.* (1983) *Lunar Planet. Sci. XIV*, 616. [18] McCoy T. J. *et al.* (1995). *Geochim. Cosmochim. Acta* (in press). [19] Dodd R. T. (1981) *Meteorites: A petrologic-chemical synthesis.* [20] Delaney J. S. *et al.* (1984) *Proc. Lunar Planet. Sci. Conf.* **15**, C251. [21] Goodrich C. A. (1992) *Meteoritics* **27**, 327. [22] Nyquist L. E. *et al.* (1993) *Meteoritics* **28**, 414. [23] Gomes C. B. and Keil K. (1980) *Brazilian Stone Meteorites.* [24] Wood C. A. and Ashwal L. D. (1981) *Proc. Lunar Planet. Sci. Conf.* **12B**, 1359. [25] Keil K. (1989) *Meteoritics* **24**, 195. [26] Watters T. R. and Prinz M. (1979) *Proc. Lunar Sci. Conf.* **10**, 1073. [2737] Casanova I. *et al.* (1993) *Geochim. Cosmochim. Acta* **57**, 675. [28] Keil K. *et al.* (1989) *Geochim. Cosmochim. Acta* **53**, 3291. [29] Longhi J. *et al.* (1992) In *Mars* (eds. H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Matthews), 184. [30] Marti K. *et al.* (1995) *Science*, submitted. [31] Warren P. H. *et al.* (1983) *Geophys. Res. Lett.* **10**, 779. [32] Bogard D. D. and Johnson P. (1983). *Geophys. Res. Lett.* **10**, 801.