The Mercury
MESSENGER

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Mercury: Planet of Fire and Ice

Part 2

Careful study of relationships between the wide range of sometimes-startling ground-based observations of Mercury's surface and atmosphere has resulted in new insights on the planet's formation and surface composition while generating interest and controversy. Observations considered here include near- and thermal-infrared spectral features, radar surface features, and atmospheric constituent abundances or limits on surface composition. These data place constraints on Mercury's bulk composition, interior structure, and geochemical differentiation.

THE SURFACE OF MERCURY

Newly Detected Microwave Surface Features: Recent global radar imaging of Mercury has been done, some of it interferometrically to allow unambiguous mapping of features, using Goldstone (with Very Large Array) 3.5-cm radar and Arecibo 12.5-cm radar facilities. This work has yielded some unexpected results [1–3]. Probably the most striking result to date is the discovery of consistently observable radar-bright features at both wavelengths, with unusually high polarization ratios at the poles. Figure 1 shows a global residual radar image, with model of reflectivity from a sphere subtracted to enhance variations. [Polarization ratios are the ratio of same sense (received as transmitted) to opposite sense (received as transmitted) radar reflectivities. Surface facets that are large relative to the radar wavelength and oriented orthogonally relative to the radar beam reflect it directly and, in the process, reverse the polarization of the transmitted signal; thus, they would be received as an opposite polarization signal. Particles that are small compared to the radar wavelength randomly scatter the signal, a process that involves internal or volume scattering and does not reverse the polarization of the transmitted signal, and would be received as the same polarization signal. The ratio of the two polarizations thus gives evidence as to the scale and degree of roughness of the surface and the nature of the materials that affect the efficiency of the scattering process.]

In other parts of the solar system, such as the poles of Mars and icy satellites, similar observations have been interpreted as indications of the presence of water ice, resulting from multiple internal scattering from density fluctuations, cracks, voids, or particles embedded in the ice. The lower reflectivity of mercurian polar features is thought to be due to a combination of the lower surface area and volume of the ice deposits and the presence of a thin dust cover. According to recent studies [4], water ice should be marginally stable in permanently shadowed areas of relatively flat-floored craters within 5° of the poles, a condition apparently observed in the correlation of the largest south polar radar feature with Chao Meng-Fu [1]. This spot apparently has a higher intrinsic reflectivity than other polar spots, possibly indicating the presence of a greater volume of ice. Other bright spots mapped near the poles are not as clearly correlated to craters that would be suitable, according to Paige et al. [3]. To survive, such deposits would need to maintain high reflectivities or be surrounded by soils with high reflectivities. Alternative hypotheses have been put forward to explain these features. Any highly reflective surface that depolarizes the radar beam efficiently due to multiple scattering in

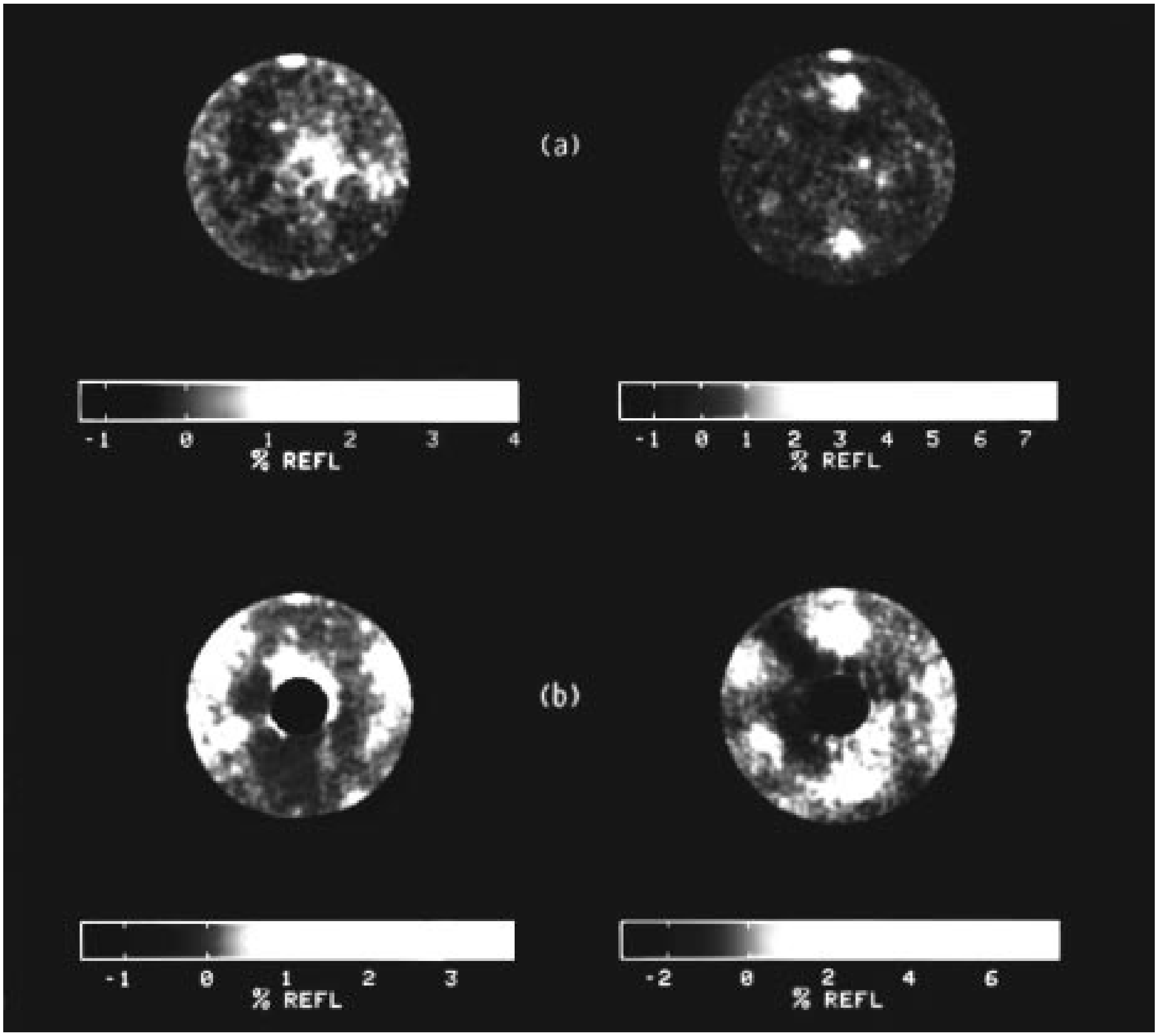

Fig. 1. From Butler et al. [2].

the subsurface (coherent backscatter) would be acceptable, according to Butler and coworkers, who suggest atmospheric deposits that form salts, such as Na, as a possibility [2]. Sprague and coworkers suggest another volatile material, S, which will be discussed in detail below [5].

Other bright features were detected at middle to upper latitudes [3]. Two bright patches with high polarization ratios, reminiscent of small impact features on the Moon, were found at approximately 350°W longitude in the unimaged hemisphere. A dark patch, which is not thought to be an impact structure, has been detected at the equator at 300°W longitude [3]. Radar altimetry and unpublished image data indicate that this dark elongated area coincides with a 2.5-km-high plateau and is heavily cratered, with a radar-bright, low-lying, uncratered, and hence younger, adjacent area to the east suggestive of volcanic, smooth plains terrain.

Thermal emission in the energy region results from the heating of grains in the top centimeters of the regolith and thus depends on the temperature and thermal inertia properties of that layer. Polarization of the emitted energies will occur to an extent that depends on the refractive index and roughness of the surface. Gehrels, Landau, and Coyne first observed regional-scale polarization differences on Mercury in 1987 [6]. Images of the polarized and unpolarized components of emissions from Mercury were taken at wavelengths ranging from 3 mm to 21 cm [7]. The dielectric constant derived from these and earlier data confirm that Mercury, like the Moon, has a low-density, particulate regolith. The polarization data are consistent with a surface that is smoothly undulating on meter scales and progressively rougher at smaller scales. There are major differences, however. The complex heating pattern of Mercury, which has alternating hot and cold poles 90° apart, was observed in these new images [7]. The transparency, or loss tangent, for Mercury is two-thirds what it is for the lunar highlands and half what it is for lunar maria [7]. Loss tangent is apparently anticorrelated with the Fe- and Ti-bearing oxide ilmenite on the Moon. This implies much less ilmenite on Mercury, which is consistent with other observations indicating a lack of Fe and Ti. Mitchell and De Pater explain thermal emission features in their images as resulting from topography and shadowing effects, which cause differential heating, and not from compositional differences. Nonetheless, they acknowledge that anomalous radar echoes could be caused by the presence of volatile components, such as water ice, in permanently shadowed polar features.

Measurements of Surface Composition: The lack of evidence for Fe and basaltic volcanism on Mercury could imply an impact, rather than volcanic, origin for major terrains, but this seems unlikely. Mercury's high mean density and relatively strong global magnetic field (implying an Fe-rich core), extensive tectonic activity as evidenced by the compressional scarp system, and relative dearth of impact basins to generate impact melt all imply extensive differentiation and volcanism. The volcanic materials are unlikely to be typified by lunar mafic basalt, as discussed below [8].

Despite the observational difficulties that result from Mercury's proximity to the Sun, intriguing groundbased measurements have been made. Radar-derived regolith conductivities lower than that of the Moon, the apparent absence of FeO, and midinfrared spectroscopic evidence for plagioclase at more than one location provide evidence that the surface is relatively low in FeO and TiO_2 [7,9–12]. Of course, elemental abundances can only be determined directly from X-ray and γ-ray spectra and such measurements can be made only if X-ray or γ-ray spectrometers are flown on future missions.

Surface mineralogy. Vilas searched many near-infrared spectral observations of Mercury for the 0.9- to 1-μm band associated with Fe^{+2} iron [10]. (The highest-resolution spectrum available from Vilas is shown in Fig. 2a.) Unfortunately, telluric water features surrounding the Fe band obscure at least part of the Fe feature, and the results are inconclusive in terms of the clear presence or absence of the band. Also, no clear differences between spectra from intercrater plains and smooth plains terrains were found. On the other hand, the spectra indicate that the regolith of Mercury is at least physically similar to lunar regolith, where the spectral slope is correlated with the presence of micrometeorite-induced agglutinitic glass-bearing Fe and Ti [9,13]. The lack of a clear Fe absorption feature suggests that Mercury's surface may be highly reduced and that it certainly lacks Fe in pyroxene, although other pyroxenes such as high-Mg enstatite may by present. This could mean either that metallic Fe is present, possibly precluded by the relatively high albedo, or that the concentration of Fe is less because most of it is in the metallic core. The reduced- or low-Fe observation is consistent with temperature-based condensation models of planetary formation and with a Mercury that is lacking in volatiles.

Sprague and coworkers made a series of mid- to thermal-infrared observations over the last decade that indicate an intermediate composition surface with plagioclase feldspar as a prominent component [11,12]. (See a comparison of Mercury and known rock powder spectra in Fig. 2b.) In the thermal-infrared region, strong absorption features known as Christensen peaks result from cool powdery surfaces, such as the Moon or Mercury, where the frequency of the refractive index for soil particles equals that of the surrounding medium. These are spectral regions of high transmission followed by absorption, maximum emission, and low reflectivity, and their exact frequency is correlated with the mineral assemblages present. Christensen peaks at both 7.9 and 7.8 μm have been observed for Mercury in regions dominated by intercrater plains, indicative of a more mafic composition similar to south polar highlands of the Moon in the first case and a more intermediate composition in the second. Later spectral observations taken simultaneously in the thermal and midinfrared indicate surfaces with a mixture of rocks and a range of basic to intermediate compositions, with Christensen peaks near or below 8 μm. When compared to a range of terrestrial rocks, meteorites, and lunar breccias, observed midinfrared spectra matched most closely a range of plagioclase feldspar compositions, from calcic to sodic, with features in one case suggesting the presence of Mg-rich pyroxene (enstatite) and olivine (forsterite), similar to an enstatite chondrite spectrum, and in the other case suggesting terrestrial basalt.

Search for sulfur. Sprague assessed the data currently available from Mercury and presented cogent arguments for the presence of S on its surface [5]. Models for Mercury's formation include strict temperature-dependent condensation/accretion, loss of accreting materials through vaporization during early stage solar heating, ejection of silicate grains by collision, or catastrophic fragmentation [14–18]. These models generally imply a refractory oxide content that is too high to be reconciled with the many observations that imply low Fe in the regolith and do not explain the planet's high density when

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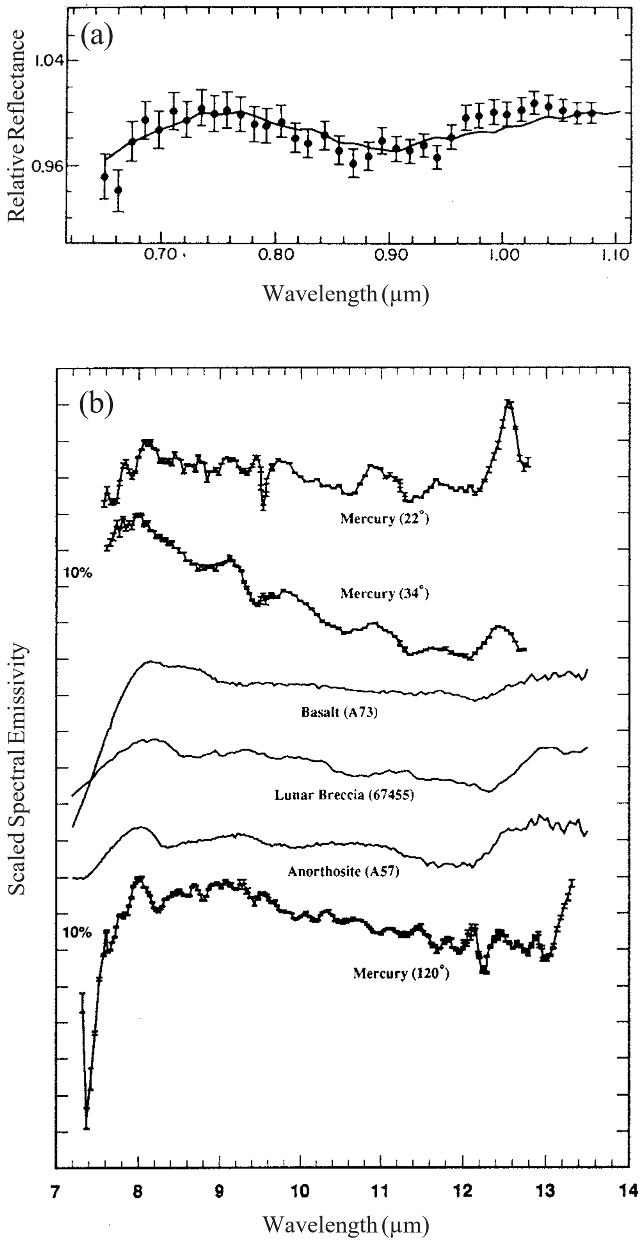

Fig. 2. **(a)** From Vilas [10]; **(b)** from Sprague et al. [11].

combined with the apparent presence of volatiles, including alkalis. Sprague prefers the suggestion by Wasson and Kallemeyn that Mercury's formation involved the accretion of enstatite chondritic matter rich in reduced S-bearing minerals such as troilite and pyrrhotite [19].

Despite the difficulty in producing a sufficiently large core with this model, it predicts high-albedo, ubiquitous low-Fe pyroxene and high-alkali feldspars, which fits current spectral observations. In addition, theoretical calculations based on whole-disk phase function indicate that Mercury's average surface material has an index of refraction considerably higher than that of the Moon, consistent with a lack of Fe and Ti and with the presence of highly reduced sulfides [20]. Mitchell and De Pater demonstrate that Mercury's regolith, even in the Caloris Region, is 1.5–2 times more transparent to microwaves (at 0.3–20.5-cm wavelengths) than the Moon's, indicating 2–3 times less Fe, Ti, and, by implication, basalt.

The implication is that early global contraction, as observed in the extensive network of compressional scarps, limited the eruption of magmas directly from the deep interior to the surface, constraining the extent of basaltic volcanism and slowing down the cooling of the interior sufficiently to allow the core to remain partially molten and to act as a magnetic-field generating dynamo. Magmas prevented from erupting directly could undergo extensive differentiation while slowly migrating upward, eventually to the surface as, for example, more alkali-rich feldspathoids [8].

Interior S would lower the temperature of dynamo-generating core formation, and S could have been outgassed during fumarolic activity to remain coldtrapped at higher latitudes, ultimately migrating to the poles. In fact, such S deposits could result in highly reflective, high-polarized radar returns such as those recently observed and are proposed as an alternative to ice as the causative agent of these features [1–3,5]. Sulfur's lower vapor pressure would enhance its survivability in this environment and thus may make it a better candidate for radar-bright spots than water ice, especially for nonpolar bright features. Sprague and coworkers [5] propose a series of observations to search for the presence of S on Mercury: in the ultraviolet at 1814 Å for atmospheric atomic S, in the midinfrared at reflectance minima 7.7 and 11.8 μm associated with elemental S, and at millimeter wavelengths for S-bearing molecules.

Implications from Atmospheric Observation: The primary constituent that would result from vaporization of water ice at the poles is OH, originally suggested as the source of radar-bright spots seen at the poles [1,3]. Killen et al. [21] suggest that an OH exosphere generated from a polar cap would be difficult to detect.

The presence of S, which has been discussed most recently as the source of the radar-bright spots at Mercury's poles [5], would explain Mercury's unique combination of surface properties. Additionally, the presence of S has been linked to lower-temperature, Fe-rich core formation and a unique style of volcanic-tectonic activity marked by inefficient mantle convection and the resulting lack of interior heat loss and large-scale basaltic volcanism. If Mercury formed in reducing conditions, it may contain significant amounts of Na, K, and Cr sulfides. An anomalously high S abundance in Mercury's atmosphere would thus be an important indicator of its formation history. A S abundance below nominal solar abundance would be a strong indication that Mercury formed in an oxidizing environment similar to that of Earth and the Moon. In this case, differentiation following accretion would have partitioned Fe, S, and some O into the core. The remaining, relatively light silicate crust could be largely composed of feldspars, minerals known to be the low-temperature condensates formed from the residual melt following fractional crystallization and solidification of a magma ocean.

According to predictions made by Killen et al. [21], Ca should be present in sufficient abundance to be observable from the Earth. Recent observations by Sprague and coworkers placing an upper limit on Ca indicate either that Ca is released less effectively from the regolith than the far more abundant Na and K from the regolith, or that its abundance is below chondritic [22]. The results of Morgan and Killen favor relatively high Na abundances [21]. Although they predict higher global Ca abundances, with more Ca present at the poles than in the equatorial region, the abundances in their models for Ca, along with Al and Fe, are still substantially lower than for Na. These findings, along with the upper limit on Li abundance determined from observations of Sprague et al., are consistent with the relative absence of Ca-rich plagioclase (anorthite) and the presence of Al and alkali-rich feldspathoids [23]. Local highs in atmospheric K or Na abundances have also been associated with geological features in the mapped hemisphere and, in some cases, radar-bright features in the unimaged hemisphere [24,25]. The association of a K high with the smooth plains in Caloris, generally thought to be volcanic in origin, provides more basis for the contention that volcanic materials on Mercury are high-alkali feldspathoids and not lunarlike basalts [24].

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Meteorites from Mercury?

Come Out, Come Out, Wherever You Are . . .

Recent compelling evidence that fragments of the Moon and Mars have fallen to Earth naturally leads to speculation about what other planets may have acted as sources for meteorites. Is it possible that pieces of Mercury arrived here? If so, how would we recognize them? How would they be classified according to present criteria, which assumes meteorites are fragments of asteroids or, in exceptional cases, pieces of the Moon or Mars? In a recent paper, Love and Keil considered these questions [1]. The likelihood of terrestrial impact of mercurian fragments, which would involve high-velocity escape followed by a series of auspicious close approaches to orient material into the proper trajectory, is about 100 times less likely than the impact of Mars material. At present, approximately 10 martian meteorites have been identified, indicating that 10 times more material would need to be sorted before a mercurian meteorite would be likely to appear.

Although we have limited information on the nature of Mercury's surface, a few generalities can be made and provide several likely specific identification criteria. Based on spectral reflectivity and photogeological evidence and knowledge of the figure of Mercury, along with generally accepted models of early solar system evolution, potential mercurian meteorites would (1) be differentiated, igneous rocks, breccias, or melts, many with evidence of volcanism; (2) probably be low in volatiles, enriched in Al, Ti, and Ca over chondritic abundances; and (3) be relatively reduced and low in Fe, with little metallic Fe. In addition, mercurian meteorites would (4) have original solidification ages that are approximately lunar (3.5–4.5 Ga), with younger impact-remelt ages possible; (5) have relatively little evidence of solar-wind implantation due to magnetic field interactions but a higher fraction of exogenic materials than lunar breccias due to greater micrometeorite flux; and (6) have uniquely high solar to galactic cosmic-ray damage track ratios due to solar proximity.

Because no one has been looking for mercurian meteorites, the possibility exists that such material has been misclassified. The closest match would be achondrites, not classes containing chondrites or irons. Aubrites, which are relatively Fe-poor, reduced, differentiated igneous rocks, would be the best match in that class, but even they might contain too much metallic Fe. Another potential match would be an anorthositic lunar meteorite that has relatively little surface exposure. Minimally, a search should be made of aubrites and the lunar meteorites to look for the unique cosmic-ray damage track ratio signatures, because to find a little piece of ground truth from Mercury would certainly be a boon in the interpretation of groundbased observations and modeling, which primarily lack compositional constraints to be completely useful. And such a search might just provide further incentive to send a mission to Mercury, or at least make the waiting more bearable.

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Note from the Editor

The editorial board consists of colleagues with a wide range of backgrounds whom I use, at least on occasion, as a sounding board for topics and content of *The Mercury Messenger*. I take full responsibility for the newsletter's final content. In particular, I would like to thank Ann Sprague and Marty Slade for input and feedback on this issue.