PRESENT BOUNDS ON THE BULK COMPOSITION OF MERCURY: IMPLICATIONS FOR PLANETARY FORMATION PROCESSES

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The bulk composition of Mercury is virtually unconstrained by the present meager data set. Compositions ranging from extremely refractory-rich to volatile-rich may be consistent with the present data. The extreme, end-member models, however, are judged implausible because the conditions under which such compositions could be produced are very restrictive and thus improbable. An intermediate, moderately refractory model for the composition of Mercury is presented. Additional data are essential for a better understanding of Mercury’s composition. Because of Mercury’s end-member position among the terrestrial planets, a better knowledge of Mercury would contribute substantially to a better understanding of the origin and composition of all of the terrestrial planets.

1. INTRODUCTION

The planet Mercury is an end member among the terrestrial planets in several fundamental characteristics, including density, mass and heliocentric distance. Because of its end-member position, Mercury provides a key test of competing models for the origin and composition of all of the terrestrial planets.

The mean density of Mercury, 5.43 ± 0.01 g cm$^{-3}$, is well determined from the observed mass and mean radius of the planet (Anderson et al. 1987). Because of its small mass, the correction of mean density to zero-pressure density is subject to little uncertainty. This zero-pressure density is about 5.3 g cm$^{-3}$, which is much higher than the zero-pressure densities of Earth and Venus (about 4.0 g cm$^{-3}$) or Mars (about 3.75 g cm$^{-3}$). The principal con-
clusion that has been drawn from Mercury's extremely high zero-pressure
density is that the planet is substantially enriched in metallic iron relative to
the other terrestrial planets (i.e., Mercury's Fe/Si ratio is higher than that of
the other terrestrial planets or solar composition material). Thermal evolution
models (see, e.g., Solomon 1976) indicate that separation of metal and sili-
cate components should have occurred in Mercury and it is thus generally
assumed to have a massive Fe-rich core which constitutes about 3/4 of the mass
of the planet.

The conclusion that Mercury is enriched in Fe is based, however, entirely
on indirect evidence (e.g., cosmochemical abundances). Based solely on the
mean density of Mercury, there are numerous combinations of heavy and light
elements that would match the mean density of the planet, and numerous core
compositions which would satisfy the density constraints (e.g., Na-U-T, Co-
W-S, Lu-V, Be-Er). The above caveats notwithstanding, the high zero-pres-
sure density of Mercury is almost certainly due to a marked enrichment of Fe
because Fe is the only heavy element sufficiently cosmochemically abundant
to constitute a major fraction of a terrestrial planet. It is with respect to iron
enrichment that Mercury is most clearly distinct in composition from the other
terrestrial planets.

If the responsible mechanism(s) were understood, Mercury's iron enrich-
ment could provide important insight into the relative efficacy of several com-
peting processes governing the formation of all of the terrestrial planets. Un-
derstanding the processes responsible for the Fe content of Mercury requires
knowledge of the bulk composition of the planet but the bulk composition of
Mercury is extraordinarily poorly constrained by present data. Compositional
extremes ranging from an extremely refractory-rich (volatile-poor) planet to a
volatile-rich (even water-rich) planet cannot be excluded on the basis of cur-
rently available, rigorous constraints on the bulk composition of Mercury.
Stated bluntly, we really know very little about the composition of Mercury
and additional data are urgently needed.

II. CONSTRAINTS ON COMPOSITION

The bulk composition of Mercury can be discussed in terms of three first-
order parameters: core composition, mantle (plus crust) composition, and
core/mantle ratio. Core composition and mantle composition are probably
coupled to a considerable extent because most processes governing composi-
tion affect both the core and mantle compositions. The core/mantle ratio,
however, could be largely or completely decoupled from the compositions of
the core and mantle because the processes governing the core/mantle ratio
(i.e., Fe/Si fractionation) may be largely separate from the processes govern-
ing composition. For example, aerodynamic fractionation (Weidenschilling
1978) or giant impacts (Chapter by Wetherill) are mechanisms which could
produce the Fe enrichment in Mercury. Fe/Si fractionation by these mecha-
nisms, however, would proceed virtually independent of the compositions of the mantle and core of Mercury. The mean density of a planet is a direct constraint on bulk composition: rock-metal, ice-rich, and gas-rich planetary bodies are readily distinguished by mean density alone. However, in the absence of further geophysical constraints (e.g., moment of inertia factor or core radius), the mean density of Mercury provides few constraints on the chemical details of composition which are necessary in order to choose between competing models. Major differences in silicate compositions (e.g., abundances of FeO, alkalis, water) which profoundly affect interpretations of planetary composition and origin, are essentially indistinguishable on the basis of mean density. Specifically, mantle compositions ranging from ultra-refractory CaO- and Al$_2$O$_3$-rich, to moderately refractory magnesium silicate (low FeO), to extremely volatile-rich (high alkalis, FeO and water) can all be accommodated by the mean density of Mercury, with suitable differences in core/mantle ratio or core density or both.

The mean density of Mercury also barely constrains the composition of the core. For example, the density of pure FeS is only about 10% less than the zero-pressure density of Mercury. Therefore, Mercury models in which the core contains substantial amounts of sulfur are completely consistent with the mean density of the planet; likewise, cores which contain substantial amounts of other possible light elements (e.g., O or Si) cannot be excluded on the basis of mean density.

The FeO content of Mercurian silicates would be one indicator of the refractory-rich vs volatile-rich character of the silicate portion of the planet because FeO abundance increases monotonically with decreasing condensation temperature in the solar nebula, and thus FeO content may be correlated with the abundances of other nonrefractory species including alkalies, FeS and water. The FeO content of surface materials on Mercury is constrained principally by Earth-based reflectance spectrophotometry data. McCord and Clark (1979) interpreted a shallow absorption feature at about 0.9 μm as due to Fe$^{2+}$ in orthopyroxenes and estimated the FeO content of surface materials to be about 5.5%. Vilas (1985) reported that the FeO band was absent from more recent spectra obtained with a high resolution CCD detector system. It appears that there is at most a few percent FeO in Mercurian surface materials and perhaps much less. Even these meager results, however, are subject to model-dependent interpretation before they can be applied to the bulk (mantle plus crust) silicate fraction of Mercury; the surface abundance of FeO could be modified by addition of FeO-rich material or by loss of FeO during an episode of volatilization of surface materials.

The bulk composition of Mercury is virtually unconstrained by the present data set. Attempting to infer the bulk composition of Mercury is thus largely a matter of building a self-consistent model for planetary origin, testing the model against planets for which more data exist, and then deducing the composition of Mercury from the postulates of the model.
III. MODELS FOR THE COMPOSITION OF MERCURY

The broad spectrum of models for the composition of Mercury which are allowed by the present constraints is outlined in the following three sections. The intent of this discussion is not to argue in detail the merits of one model vs another, but rather to summarize the implications of the various models for the composition of Mercury and to emphasize the wide range of possible models.

Extreme End-Member Models

The assumption that Mercury is a refractory-rich, volatile-poor planet has been widely held for at least the past decade (see, e.g., Kaula 1976). This assumption appears to be based in large part on the pioneering work of Lewis (1972, 1974) in which he derived models for planetary compositions which were based on calculations of condensation in the solar nebula. The basic premise in Lewis' work is that heliocentric gradients in temperature and pressure in the solar nebula produced heliocentric gradients in the composition of condensed material in the nebula, and that such compositional gradients are preserved in the present bulk compositions of the planets. In the extreme, end-member case of this model, Mercury is an extraordinarily refractory planet because the silicate component must be only partially condensed and thus only extremely refractory components are incorporated into Mercury. The Mercury composition predicted by this end-member model is shown in Table I. The silicate component is very high in Al₂O₃, CaO and TiO₂; high in MgO.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>COMPOSITION OF MERCURY, wt.%</th>
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<tr>
<td></td>
<td>Extreme Refractory-Rich Model</td>
</tr>
<tr>
<td>Muzzle*</td>
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</tr>
<tr>
<td>Al₂O₃</td>
<td>16.62</td>
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<tr>
<td>CaO</td>
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<td>TiO₂</td>
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<td>MgO</td>
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<tr>
<td>SiO₂</td>
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<tr>
<td>FeO</td>
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</tr>
<tr>
<td>Na₂O</td>
<td>0</td>
</tr>
<tr>
<td>H₂O</td>
<td>a little</td>
</tr>
<tr>
<td>Core</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>92.48</td>
</tr>
<tr>
<td>Ni</td>
<td>7.53</td>
</tr>
<tr>
<td>S</td>
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</tr>
</tbody>
</table>

*Plus crust (i.e., bulk silicate fraction of Mercury).
relative to SiO$_2$ because of incomplete condensation of silicates; and essentially devoid of FeO, alkalis, water and other volatile species. The core is essentially pure Fe-Ni alloy without S, Si or O.

The antithesis of the refractory-rich model for the composition of Mercury is that Mercury is a refractory-poor, volatile-rich planet. The consensus that Mercury is a refractory-rich planet has been so widespread that the possibility that Mercury could be volatile-rich has not been considered seriously, even though such a model is entirely consistent with the observed mean density of the planet. A volatile-rich model for Mercury is presented in Table I. This model composition for Mercury assumes that the silicate portion of Mercury has the same composition as the Mars model computed by Goettel (1983). This Mars model assumed that Mars was composed of the solar proportions of the major rock-forming elements, with the oxidation state of Fe (i.e., the FeO to total Fe ratio) adjusted to produce mantle and core densities and a mantle/core ratio consistent with the rigorous bounds derived by Goettel (1981). Wänke and Dreibus (1985) presented a similar model for the composition of Mars which was based on the interpretation of Mars as the SNC meteorite parent body. Thus, the volatile-rich model composition given in Table I appears to be a reasonable approximation to current understanding of the composition of moderately volatile-rich material in the inner solar system (i.e., Mars-like material). In this model, the core of Mercury would be high in S and larger than pure Fe-Ni cores; the mantle would be high in FeO and alkalis and contain substantial amounts of water and other volatiles.

Mercury could possibly have a Mars-like composition (albeit with a separate mechanism for Fe/Si enrichment) if mixing were sufficiently vigorous in the solar nebula during the accretion process to homogenize the formation region of the terrestrial planets compositionally. This possibility is admittedly extreme (i.e., there is some evidence supporting a compositional gradient within the terrestrial planet group); however, the homogeneous terrestrial planets hypothesis cannot be excluded if one allows a few additional assumptions. For example, the difference in FeO content between the Earth's mantle (about 8%) and the Martian mantle (about 15%), one of the benchmarks of a compositional gradient among the terrestrial planets, can be eliminated if the Earth's mantle originally had about 15% FeO with the excess above the present upper mantle abundance either sequestered in the lower mantle or incorporated into the Earth's core. Likewise, the spectrophotometric evidence suggesting low FeO content on the surface of Mercury is somewhat ambiguous. Even if the surface of Mercury were proven to have virtually no FeO, however, it is still possible that the interior could be FeO-rich if the surface were depleted by a volatilization episode. If the volatile-rich model is carried to its logical extreme, then Mercury could potentially be the most volatile-rich terrestrial planet (e.g., if stochastic fluctuations in the accretion process resulted in Mercury's accretion of a large protoplanet formed originally in the outer fringes of the terrestrial planets' accretion zone).
Moderately Refractory-Rich Models

There are three major groups of models which predict a moderately refractory-rich Mercury:
1. Variations of Lewis' (1972, 1974) condensation temperature model;
2. Models requiring the post-accretion loss of a significant fraction of Mercury's silicate component by volatilization (Ringwood 1966; Cameron 1985; Fegley and Cameron 1987) or by giant impact (see, e.g., Chapter by Wetherill 1987);
3. Models based on incorporation of highly reduced, refractory components (see, e.g., Morgan and Anders 1980; Winke and Dreibus 1986; Chapter by Wasson 1987).

These groups of models are discussed briefly below.

The original condensation temperature model for the composition of Mercury (Lewis 1972) attempted to explain both the composition of the silicate portion of Mercury and the Fe/Si ratio by a single (very narrow) condensation temperature and pressure for the material constituting Mercury. In its end-member form, this model is not plausible because of the inevitability of temporal and spatial gradients in the composition of condensed material, and because of the finite (perhaps large) width of the accretion zone feeding the growing planet Mercury. Developments in the understanding of the accretion process (see, e.g., Hartmann 1976; Cox and Lewis 1980; Chapter by Wetherill) indicate that material accreted by Mercury cannot originate only in immediate proximity to Mercury, but must also include material in model-dependent proportions from the entire region of the terrestrial planets. Barshay (1979) examined the compositional implications of a finite feeding zone for Mercury and concluded that the extreme Fe content of Mercury cannot be explained simply by accretion of ultra-refractory, silicate-poor material; rather, some physical process of Fe/Si separation is required to account for the high density of the planet.

There are three principal effects of relaxing the end-member assumptions in the condensation-temperature model for Mercury. First, the proportion of Fe in the condensate drops sharply as silicates are fully condensed. Second, the Mg/Si ratio drops rapidly towards the solar system value as Si condenses fully (in a mixture increases at the expense of forsterite). Third, the abundances of nonrefractory species (alkalis, FeS, FeS, water and other volatiles) increase gradually, with a corresponding gradual decrease in the proportions of the more refractory species. Lewis (see his Chapter) has extensively explored the relationships between accretion sampling algorithms and the predicted composition of Mercury by assuming Gaussian sampling functions (centered near Mercury's heliocentric distance) and varying the half width of the sampling distribution. Lewis' quantitative results map out a spectrum of models in multidimensional composition space ranging from the end-member, extremely refractory model to moderately refractory models; this spectrum of composition models varies principally in the three ways listed above.
The second group of models which predict a refractory-rich Mercury includes models invoking post-accretion loss of a substantial fraction of Mercury’s silicate component either by volatilization from the surface or by giant impact. Surface-volatilization models (see, e.g., Ringwood 1966; Cameron 1985a; Poggey and Cameron 1987) drive whatever the initial composition of Mercury was towards the refractory direction; that is, the volatilization processes, whatever the detailed mechanism(s), deplete Mercury in volatile components such as alkalis, FeS, FeO and water. In chemical detail, the resulting composition varies in a model-dependent manner; qualitatively, however, the range of compositions predicted by volatilization models maps out a spectrum quite similar to the spectrum of models presented in the Chapter by Lewis.

The chemical effects of removing a substantial fraction of Mercury’s silicate component by giant impacts are somewhat less clear. Lewis (his Chapter) suggested that abundances of refractories would not be greatly enhanced by a giant impact event because ejection of a feldspar-rich crust would deplete CaO and Al₂O₃ along with alkalis and that the FeO content after impact would reflect the primordial oxidation state of the planet at the time of accretion. However, recent analyses of the physics of giant impacts suggest that extensive melting and vaporization of material occur during the event (Benz et al. 1987). Thus, it appears probable that substantial loss of volatile and moderately volatile species would occur during a giant impact event. The chemical effects of giant impacts, while differing in details from the effects of volatilization, will also drive Mercury in the refractory-rich direction.

The third group of refractory-rich models for Mercury are those in which the refractory nature of Mercury is a postulate of the model. Morgan and Anders (1980) computed a detailed model for Mercury, based on their seven-component model for planetary compositions. In this model, Mercury is moderately refractory, with a mantle FeO content of 5.5% based on the spectroscopic results of McCord and Clark (1979). Wänke and Dreibus (see their Chapter) suggested that Mercury could be highly reduced with Si incorporated into the core; their model assumes a composition similar to that of the enstatite chondrites. Wasson (see his Chapter) also suggested that enstatite chondrites may be a good model for the composition of the silicate component of Mercury. This group of models is more eclectic than the groups discussed previously; nevertheless, despite some differences (e.g., the presence of reduced Si in some models), the range of compositions predicted for Mercury by this group of models follows the general trend of the spectrum of compositions mapped out in the Chapter by Lewis.

Preferred Model

The extreme, end-member models for the composition of Mercury are implausible because the circumstances under which such compositions would be produced during the formation of the terrestrial planets are very restrictive. More plausible, and thus preferred, models lie between the extremes (i.e.,
that Mercury is somewhat enriched in refractories, but not nearly as enriched as in the end-member, refractory-rich model. The preferred model that is presented in Table I is based on the following assumptions.

1. The three most refractory components (Al$_2$O$_3$, CaO, TiO$_2$) are not fractionated with respect to each other because they were fully condensed in all regions from which Mercury accreted material.

2. The three most refractory species are moderately enriched above solar proportions (i.e., the Al/Si, Ca/Si and Ti/Si ratios are greater than the solar ratios) because Mercury accreted some material in which magnesium silicates were only partially condensed.

3. The Mg/Si ratio in Mercury is somewhat higher than the solar value because the refractory condensates are enriched in Mg and correspondingly depleted in Si. The Mg/Si ratio, however, is near the solar value because Mg and Si were both fully condensed in the regions from which Mercury accreted most of its material.

4. Mercury contains significant amounts of moderately volatile components, including alkalis, FeO, FeS and water. The absolute abundances of these components, as well as their relative proportions, are strongly dependent on the extent of mixing of materials from different heliocentric distances and thus are poorly determined.

5. The Fe/Si ratio of Mercury was increased by a physical mechanism, perhaps aerodynamic fractionation (Weidenschilling 1978) and/or giant impact (Wetherill 1987), which operated largely independently of the composition of the silicate component of Mercury.

The preferred model for Mercury is a moderately refractory composition, with refractory components (e.g., Al$_2$O$_3$, CaO, TiO$_2$) enriched above solar proportions and with moderately volatile components (e.g., alkalis, FeO, FeS, water) significantly depleted below solar proportions. The core of Mercury contains much less than the solar proportion of S relative to Fe, but enough S to affect the thermal evolution of the core (in particular, enough S to prevent complete freezing of the core).

This preferred model was framed in the context of the condensation-temperature model for composition gradients in the solar system. The intent in presenting it was not, however, to exclude other models from consideration. The ranges of compositions presented in this model can also be produced by models in which surface volatilization and/or giant impacts have modified the original composition of Mercury and by models incorporating moderately refractory components into Mercury.

IV. CONCLUSIONS

The present data base for Mercury is so limited that virtually no rigorous bounds can be placed on the bulk composition of the planet: compositions
ranging from extremely refractory-rich to volatile-rich may be consistent with the limited data. It is important to note that many of the models discussed are not mutually exclusive. For example, Mercury could have had an initial composition governed by accretion sampling of materials from various heliocentric distances, with the Fe/Si ratio determined by aerodynamic fractionation, and the original composition modified by episodes of surface volatilization and giant impacts.

Mercury, because it is an end-member terrestrial planet with respect to heliocentric distance and density, has the potential to be a key indicator of the processes governing the formation and composition of all of the terrestrial planets. Acquisition of additional data is absolutely essential for a better understanding of the composition of Mercury. Quantitative data from a Mercury mission including orbiter and lander chemical analyses, determination of the moment of inertia factor and (ideally) seismic profiling of the interior would vastly increase our understanding. The direct relevance of a better understanding of Mercury to a better understanding of the processes governing the origin, composition and evolution of all of the terrestrial planets suggests that a Mercury mission should have a very high priority.