EFFECTS OF OXIDATION ON BUILDING ROCKY PLANETS: FROM MERCURY TO A CORELESS TERRESTRIAL PLANET.

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Introduction: Differentiation in terrestrial planets is expected to include the formation of a metallic core. We suggest that oxidation state during accretion and solidification may determine the size of any metallic core, and we predict the existence of terrestrial planets that have differentiated but have no metallic core. Under this hypothesis, any metallic iron in the bulk accreting material is oxidized by water, binding the iron in the form of iron oxide into the silicate minerals of the planetary mantle. The planet becomes effectively a giant silicate mantle without a metal core. In this case, planetary differentiation will involve only silicates and volatiles. Conversely, unusually reducing conditions near the Sun may have produced the large core fraction of Mercury.

The existence of coreless silicate planets or planets with large cores has consequences for interpreting the compositions of exoplanets based on their mass and radius, because average density, density gradients, and therefore moment of inertia factor will differ from those of the Earth or Mars.

Models: The underlying assumption for the model is that bodies are accreted from planetesimals that originated at a range of orbital radii [1-6]. Because material from larger orbital radii is likely more water-rich, this scenario raises the possibility that outer solar-system material may oxidize the reduced, metallic material from the inner solar system.

Planets are assumed to have formed from materials similar to the chondritic meteorites from the collection of falls found on Earth. These meteorites represent primitive, undifferentiated material from the time of planetary accretion. A simple inverse relation that exists between metal and water in chondrites invites the description of a coreless terrestrial planet: the chondrites with water contents approaching zero (those with the least alteration) have the largest metallic iron fractions. Those with high water contents have little or no metals. High metal examples can contain metallic iron and nickel approaching 70 mass% [7,8], while Wood [9] reports up to 20 mass% of water in chondrites with little or no metals.

We assume in all cases that the bulk silicate planet has melted from the combined effects of heat of accretion. We calculate mineral compositions in equilibrium with the magma ocean composition. For further details see Elkins-Tanton & Parmentier [10] and Elkins-Tanton [11].

Solidification produces a density profile in the planet that is compositionally unstable to gravitational overturn through processes of iron enrichment during progressive solidification from the bottom of the mantle upward. The unstable material can flow in the solid state to gravitational stability, with higher-iron compositions at lower planetary radii. This critical step in planetary evolution from a magma ocean stage results in a mantle that is gravitationally stable, with densest silicates lying at lowest radii, and most buoyant silicates nearest the planetary surface. Thus planetary differentiation includes not only separation of metallic from silicate stages, but also compositional separation of silicates.

Reducing followed by oxidizing conditions: The metallic cores of the terrestrial planets require that early accretion occurred in a reducing environment. The Earth and Mars (and perhaps Venus) later obtained a significant water content, possibly by later accretion of hydrous materials [12-15], or possibly from water adsorbed from the planetary nebula onto small, undifferentiated accreting materials [16-18].

For this scenario, where initially reducing conditions are followed by oxidizing conditions, the planet is assumed to have a metallic core the mass fraction of the Earth's, and a mantle of bulk Hart and Zindler composition [19]. The Earth-mantle composition produces a planet with a dense core and a low-density mantle. The metallic core has a density on the order of 8,000 kg/m^3. The silicate mantle's density averages about 5,000 kg/m^3 less than the core, and density range within the silicate mantle itself is only 400 kg/m^3 (Fig. 1).

Oxidizing conditions: We hypothesize that there are two accretionary paths to a coreless planet. In the first, the planet accretes from material that was fully oxidized before accretion. In the second hypothesis, the planet accretes from both oxidized and reduced material, and oxidation of metals occurs in a well-mixed magma ocean or partially-molten slurry.

Using average chondrite class compositions as simple illustrative end-members, complete iron oxidation for metallic iron-rich compositions can require up to approximately 20 mass% of the planet in additional oxygen. If volatile-rich comet-like solar system material is roughly half water, then to fully oxidize a planet that begins with the highest fraction of iron metal requires the final planet to consist of roughly 40% volatile-rich added material. Planets may be expected, therefore, to attain varying degrees of oxidation depending upon the oxidation states of their accreting material and the degree of mixing the accreting material experiences.

For the fully oxidized case, we use an average EH chondrite with all iron oxidized to FeO. Each of these compositions and levels of reduction are used to build a Mars-sized planet. The fully-oxidized, coreless planet has a silicate density range of about 600 kg/m^3 from the planet's center to its surface. Thus with approximately the same bulk compositions, the two planets produce vastly different density profiles. Each ends with a gravitationally stable silicate mantle, though the coreless planet has a far more stable silicate density gradient, which is therefore far more resistant to onset of thermal convection.

A coreless silicate planet will have an average uncompressed density higher than a similarly-composed planet with a core, and its moment of inertia factor will be higher. In the examples here, the coreless planet has an average uncompressed density of 3,544 kg/m^3, while the silicate planet with a metallic core has an average uncompressed density of 3,420 kg/m^3; its average silicate mantle density is only 3,070 kg/m^3 (Fig.1).

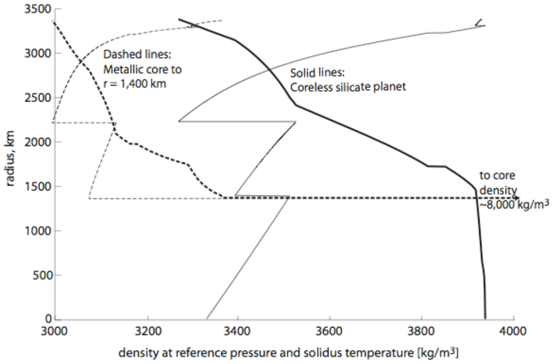

Figure 1: Density as a function of radius for two planetary models. Dashed lines: Metallic core to ~40% of planetary radius, and then Earthlike [19] mantle composition (Table 1). Solid lines: Average EH chondrite composition, fully oxidized, over entire planetary radius. Fine lines indicate the unstable density gradient of silicates differentiated in magma ocean solidification, and bold lines indicate the stable silicate planet following overturn of the magma ocean differentiates.

Reducing conditions: If the highest-iron chondrite composition now known, the CB chondrites, is reduced until all iron oxide resides in the core as iron metal, the resulting planet has a core fraction of 60 to 70 mass% of the planet (see Brown and Elkins-Tanton, this meeting). These conditions may be expected to exist closest to the star, where temperatures are highest and accretion very swift.

Moments of Inertia: The moment of inertia factor can be measured remotely for solar system planets and is therefore of use in discriminating internal structures and comparing among planets of different sizes and masses. The planet formed under the most reducing conditions, with a core radius of 75% of the planetary radius, has a moment of inertia factor of 0.34. The planet with a metallic core has a moment of inertia factor of 0.364, while the coreless planet's is 0.391, a significant difference. These model results are in good agreement with known moment of inertia factors: the Moon's moment of inertia factor is 0.392, indicating a small or nonexistent metallic core. The Moon's silicate interior is known to be differentiated. The next largest moment of inertia factor of the terrestrial planets is Mars', at 0.366 [20]. Earth's, Venus', and Mercury's are all near 0.33, Io's 0.377 [21] and Callisto's 0.359 [22].

Conclusions: Beginning accretion with material already oxidized, or oxidizing material during accretion by accretion of heterogeneous material, imply the possibility of planets with a full range of metallic core masses, from zero to the maximum metallic iron available (which in the solar system is currently the CB chondrite, with as much as ~70 mass% metallic iron, equivalent to the core mass of Mercury). If the most reducing conditions existed closest to the Sun and the most volatile-rich at increasing radius from the Sun, then the terrestrial planets' core masses might be expected to follow this trend, which in fact they do. Mercury, closest to the Sun, has a core equal to 60 to 70 mass% of its planetary mass, while the Earth's is ~32 mass% of the planet, Venus' ~25 mass%, and Mars', only 15 – 20 mass%. This increase of silicate mass of the planet with radius supports the possibility of a coreless silicate planet at larger orbital radii.

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