THE LOSS OF MANTLE MATERIAL FROM MERCURY. A.G.W. Cameron, Harvard-Smithsonian Center for Astrophysics.

Mercury shares with the Moon the possession of a composition that differs greatly from the normal for terrestrial planets, but these two bodies lie at opposite ends of the composition spectrum. The Moon is highly depleted in metallic iron, but Mercury has a large surplus of the stuff. It has long been recognized that some sort of special event was probably responsible for the origin of the Moon, and many contending theories have been thrown in the ring. It is equally apparent that some unique circumstance is required to explain the anomalous composition of Mercury, but so far the theories have been conspicuous by their absence.

My own work on the primitive solar nebula has now led to the prediction of a high-temperature environment in the solar nebula during the final stages of formation of the Sun, and I expect a temperature in the vicinity of the distance of formation of Mercury to be probably in the range 2500 - 3500 K. This temperature is high enough to volatilize all elements and their compounds, and questions must be raised about the stability of bodies of planetary size, particularly rather small planets such as Mercury. The results of the calculations to be described indicate that Mercury has probably lost a large amount of silicates from its mantle by volatilization and blow-off in a planetary wind.

The estimated uncompressed density of Mercury is 5.3 gm/cm^2, while that of the Earth is only 4.04 gm/cm^2 (1). Strom (1) has estimated that the iron core of Mercury is about 70 percent of the mass of the planet, which is more than twice as great as that of any other known planet. This suggests that one could reconstitute a hypothetical original Mercury of normal chondritic composition that would be about 2.25 times the present mass. I have studied the blow-off of simple rock decomposition products from this hypothetical planet, as well as from the present planet and also from a hypothetical protovenus. The loss of metallic iron from the present Mercury was also studied.

It must be emphasized that the scenario discussed here is not consistent with the popular picture in which the planets are entirely assembled starting from small planetesimals. The dissipation of the solar nebula involves a vigorous convection and turbulent viscosity (2), and until the Sun can be formed and the radiation from it can stabilize the nebula so that turbulence dies away (3), small particles cannot precipitate to midplane to form a thin layer which will be unstable against the gravitational formation of asteroidal-sized bodies (4). Thus the high temperature stage of the solar nebula is over before the planetesimals exist. I expect the very earliest stage in the formation of the solar nebula to be unstable against gravitational instabilities in the gas (3), forming giant gaseous protoplanets, which soon have their envelopes evaporated by the rising nebular temperature (5), but which may be able to leave residues in the form of precipitated condensed matter. Such refractory residues should form the bulk of the terrestrial planets, and it is just such an object that I have in mind as the hypothetical original Mercury which was exposed to the high temperature phase of the solar nebula.

In a massive blow-off in the form of a planetary wind the gas is accelerated through a critical point where the velocity becomes supersonic. This solution was originally found for inflowing gases by Bondi (6) and later applied to the solar wind by Parker (7). I have assumed the supersonic solution beyond the critical point, whose position depends on the temperature, planetary mass, and the mean molecular weight of the gas, and I have taken the exterior environment to be isothermal at the assumed solar nebula temperature. Interior to the critical point the problem involves structure and energy transport equations to which are added various transport terms dependent on the motion of the gas. The parameters to be adjusted to give a self-consistent solution include the mass loss rate and the inward energy transport rate from the surrounding solar nebula. The radiative conductivity dominates. The solutions must be determined between the critical point and the planetary surface, and the inner boundary conditions to be fitted include the equivalence of the surface gas pressure and the vapor pressure of the condensed phase under consideration, and the equivalence of the inward energy transport at the planetary surface with the energy requirement for vaporizing just enough condensed material to replace that being lost in the planetary wind.

The calculations assumed a simple rock type for this initial investigation. Since magnesium and silicon are of approximately equal abundance, I chose $MgSiO_3$ as a suitable compound. This is dissociated into the following components:

$$MgSiO_3(liq) = Mg(g) + SiO(g) + O_2(g).$$

An important physical property in the problem is the opacity of these gases, which is unknown. Calculations were done with opacities of 1.0, 0.1, and 0.01 cm^2/gm. I prefer the lowest of these opacities since these simple gases absorb only weakly in the infrared at temperatures near 3000 K. Fortunately it turns out that the interesting solutions are then not very dependent on the value of the opacity. Although all of the solutions will be published, I give here only those for the lowest opacity. The time scale appropriate to the high temperature phase of the solar nebula is about 2×10^4 years, and I shall concentrate on the conditions in which one Mercury mass of material can be blown off in that time.

For the hypothetical original Mercury with 2.25 times the present mass of that planet, the blow-off at the target rate occurs at a solar nebula temperature of 3400 K, which is within the expected band of temperatures. For the present Mercury the blow-off of a Mercury mass occurs in 2×10^4 years at 3000 K, and at 3400 K the blow-off of a Mercury mass takes 2.7×10^3 years. From these numbers it may be seen that if the planetary mass loss becomes significant, the rate accelerates, and for a given set of environmental conditions the evaporating constituent is likely to be completely lost by these simple considerations. I also computed the rate of loss of metallic iron from the surface of the present Mercury. Here the characteristic times for blow-off of a Mercury mass are 6×10^4 years at 3400 K and 2×10^6 years at 3000 K. On this simple picture the iron core would survive, but there is only a narrow temperature range which ould allow it to do so.

The actual situation is likely to be considerably more complicated. Calcium and aluminum oxides and silicates such as compose inclusions in meteorites are an order of magnitude less abundant than magnesium silicates in the mantle of a terrestrial planet, and they have a much reduced vapor pressure compared to iron. Therefore at the least they would provide a scum floating on top of a Mercury iron core that would protect that core from evaporation. Bruce Fegley has pointed out to me that the solution of these substances in a magnesium silicate lava will reduce the vapor pressure of the magnesium silicate decomposition products. This is unlikely to have much effect on the loss of magnesium silicates in the early stages, but it is likely to be able to protect a significant amount of them toward the end when their abundance has significantly decreased. Thus it is not clear whether the present 30 percent of the mass of Mercury that is in the mantle has mostly survived the period of the heat bath or whether the bulk of it has collected afterwards from the collisions of small planetesimals with Mercury.

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