MERCURY: A PREDICTION FOR BULK CHEMICAL COMPOSITION, PHYSICAL STRUCTURE AND ORIGIN.

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Introduction: The fast approaching first flyby of Mercury by the NASA MESSENGER spacecraft on 15 January 2008 has aroused fresh interest in this mysterious planet. Perhaps the most unusual feature of Mercury is its high mass density $\sim 5.43 \pm 0.01 \, \text{g/cm}^3$ [1]. Even after the effects of compression due to self-gravity are removed, the resulting density is still ~ 5.30 g/cm^3. This implies a metal mass fraction of 0.67 which is more than twice that of Venus. This feature, coupled with many other marked trends with orbital distance in the bulk chemical compositions of the 4 terrestrial planets, points strongly to the conclusion that: (i) there existed well-defined gradients of temperature and pressure within the solar nebula gas from which the planets condensed, and (ii) each planet accreted mostly from material that had condensed close to the present orbits. That is, each planet 'received the overwhelming majority of its mass from narrow, compositionally-distinct annuli of material around the Sun' [2]. Such an outcome arises naturally if the planetary system had formed from a family of isolated gas rings, as is the basic premise of the the Modern Laplacian theory of Solar system origin (hereafter MLT – see below) [3-5].

Within the MLT, the reason why Mercury is so metal rich is simply that the temperature of its formative gas ring was so high that only metals were able to condense out in any appreciable amount. The normally dominant Mg-bearing silicates were depleted since Mg remained mostly in the vapour phase. Such a metal-silicate fractionation process was first noted by Lewis [6]. It is readily quantified within the gas ring model scenario [7, 8]. In this paper, I construct a detailed thermal and structural numerical model for Mercury that is based on the bulk chemical composition that derives from the MLT.

The Modern Laplacian Theory: According to the MLT, the planetary system condensed from a concentric family of orbiting gas rings. These rings are shed by the contracting protosolar cloud (PSC) as a means for disposing of excess spin angular momentum during gravitational contraction, starting first at the orbit of Quaoar ($R_0 = 9323 R_\odot$, where $R_\odot = 6.9598 \times 10^{10}$ cm). If R_n and M_n denote the equatorial radius and mass of the PSC after shedding the nth of mass m_n ($n = 0,1,2...$) and f_n is the cloud's axial moment-of-inertia (MOI) factor, then conservation of angular momentum gives $R_n/R_{n+1} = (1 + m_{n+1}/M_{n+1}f_{n+1})^2$. The temperature T_n on the mean orbit of a ring scales

as $T_n \propto M_n/R_n$. The gas pressure on the mean orbit of the gas ring is $p_n = \rho_n \Re T_n/\mu$, where $\rho_n \propto m_n/R_n^3$ is the gas density and μ is the mean molecular weight.

If the PSC contracts homologously, so that m_n/M_n and f_n stay constant, then the R_n form a geometric sequence. The precise values for T_n and p_n depend on the controlling parameters of the PSC. These are chosen so that (i) the mean orbital spacings of the gas rings from Jupiter to Mercury matches the observed planetary spacings, and (ii) that the condensate bulk density ρ_{cond} at Mercury's orbit is 5.30 g/cm^3. In the diagram below, the heavy yellow locus shows a plot of the gas ring temperature versus orbital distance at the times of detachment of the rings. Also plotted are the condensation temperatures $T_{i,n}$ of the principal chemical species ($i = 1, 2, 3...$). These are computed for the pressure p_n on the mean orbit of the local gas ring.

CHEMICAL CONDENSATION SEQUENCE
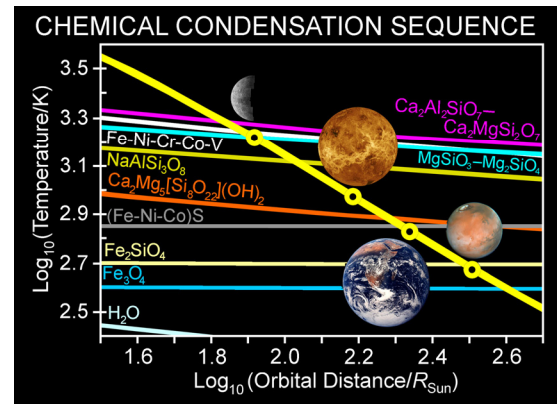
Properties of the Protosolar Gas Rings: The table below gives the initial orbital radii $R_{n,i}$ of the gas rings from which the planets formed as well as the present orbital radii R_n. The loss of cloud mass during contraction results in the subsequent secular expansion of each gas ring and its condensate stream after ring detachment. We have $R_n = (M_n/M_\odot)R_{n,i}$, where M_n is the PSC mass at the moment of detachment t_n. This is also given. It is the time taken for the PSC to contract to equatorial radius R_n from an assumed initial radius $R_i = 1.2 \times 10^4 R_\odot$, where $M_i = 1.211 M_\odot$. For Jupiter we have $M_n = 1.165 M_\odot$ and for Mercury $M_n = 1.081 M_\odot$. The last 2 columns give the temperature T_n and mean orbit pressure p_n of each gas ring at time t_n.

A view of the gas ring that is cast off at Mercury's orbit is shown below. The gas pressure at distance ξ

off the mean orbit is $p_{\text{gas}}(\xi) = p_n \exp(-\frac{1}{2}\alpha_n\xi^2/R_n^2)$, where $\alpha_n = \mu GM_n/\Re T_n R_n$ is a constant. We assume that only 2 condensing species are present. These are Fe $(i=1)$ and MgSiO$_3$ $(i=2)$. The main feature to note is that after condensation has occurred, the solid grains settle onto the mean orbit R_n to form a concentrated stream. This 'focussing' property of the gas ring is a basic feature of the modern Laplacian theory [3]. As there is no exchange of condensate material between adjacent gas rings, the chemical composition of each planet is uniquely determined by the thermal properties of its own formative ring. Next, condensation is restricted to minor radii $\xi < \xi_i$ where the partial pressure of species i exceeds the vapour pressure $P_{i,\text{vap}}(T_n)$. As $P_{1,\text{vap}}(T_n) << P_{2,\text{vap}}(T_n)$, Fe condenses throughout most of the ring but MgSiO$_3$ condensation occurs only near the mean orbit ($\xi = 0$). As a result, the condensate is deprived of silicates relative to metal [7, 8].

Gas ring properties for the terrestrial planets

Planet	R_n/AU	$R_{n,i}$/AU	t_n/10^5yr	T_n/K	p_n/bar
Mercury	0.387	0.358	3.54	1628	0.168
Venus	0.723	0.654	3.46	910	0.0157
Earth	1.000	0.895	3.40	673	4.6×10^{-3}
Mars	1.524	1.343	3.32	454	9.3×10^{-4}

The Predicted Bulk Chemical Composition: The predicted chemical makeup (and mass fractions) for Mercury are: Fe-Ni-Cr-Co-V (0.6709), Ca$_2$Al$_2$SiO$_7$ (0.1896), MgSiO$_3$-Mg$_2$SiO$_4$ (0.0814), MgAl$_2$O$_4$ (0.0377), Al$_2$O$_3$ (0.0120), CaTiO$_3$ (0.0084). The RTP condensate density is $\rho_{\text{cond}} = 5.30$ g/cm^3. No sulphur is present in the mix.
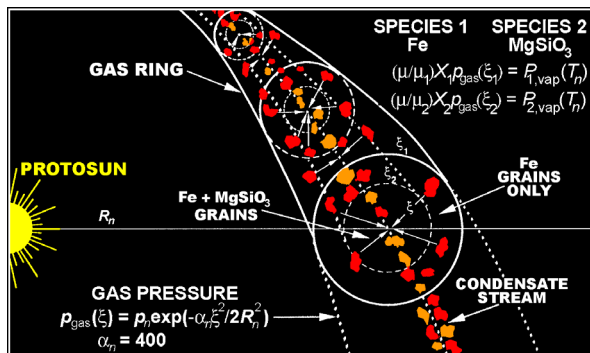
A Computed Thermal and Structural Model: Next, a differentiated 2-zone model for Mercury has been constructed on the basis of the above bulk chemical composition. The adopted planet physical radius is 2440 km. First, the present-day internal temperature profile was obtained by thermally evolving the planet for 4.6 Gyr, taking into account the heat released by the decay of the radioactive isotopes of U and Th in the rocky mantle. No K^{40} is present in the rock. The rate of conductive heat transfer in the rock is controlled by the principal species, namely gehlenite. This has a very low thermal conductivity [9]. The maximum value occurs at ~850 K and is ~3 W m^{-1} K^{-1}. Much of the mantle, from the edge of the metal core out to the 93% mass point is thus convective. Convection is modelled using a solid-state creep formalism. The rock is assumed to convect as soon as the temperature exceeds a value $T_{\text{creep}} = 0.7T_{\text{melt}}$ [4]. Here T_{melt} is the local melting temperature. As no high pressure melt data is available for gehlenite, I have adopted the liquidus data for MgSiO$_3$. The hottest point in Mercury is at the core boundary, where $T = 1630$ K. The temperature at the edge of the convective layer is 1375 K, while at the centre of the metal core it is only 1000 K. The adopted surface temperature is 350 K.

Lastly, a structural model for Mercury was computed using the above thermal profile. The core has a uniform temperature of 1430 K. The rocky mantle has a uniform temperature of 1510 K for the convective region and 840 K for the outer conductive layer. The central pressure of Mercury is 42.4 GPa and the mean density is 5.42 g/cm^3. The core radius is 1849 km and the axial MOI factor is $C/MR^2 = 0.3265 \pm 0.002$. This agrees well with an earlier estimate [10]. Today, the planet is predicted to be solid, having no liquid layers. The present magnetic field may thus be a fossil field left over from an ancient warmer period in the planet's past, when a strong dynamo once existed.

References: [1] Anderson J.D. et al. (1987) *Icarus*, 71, 337–349. [2] Drake M.J. and Righter K. (2002) *Nature*, 416, 39–44. [3] Prentice A.J.R. (1978) *Moon Planets*, 19, 341–398. [4] Prentice A.J.R. (2001) *Earth, Moon & Planets*, 87, 11–55. [5] Prentice A.J.R. (2006) *Publ. Astron. Soc. Australia* (*PASA*), 23, 1–11. [6] Lewis J.S. (1972) *Earth & Planet. Sci. Letts.*, 15, 286–290. [7] Prentice A.J.R. (1991) *Proc. Astron. Soc. Aust.*, 9, 321–323. [8] Prentice A.J.R. (2001) In *Workshop on Mercury*, 81–82, LPI Contribution No. 1097, LPI, Houston. [9] Steadman E.N. et al (1992) 12th Annual Gasification & Gas Stream Cleanup Contractors Review Meeting, Morgantown, WV. [10] Siegfried R.W. and Solomon S.C. (1974) *Icarus*, 23, 195.