METAL/SILICATE FRACTIONATION IN THE SOLAR SYSTEM

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Fractionation between the metal and silicate components of objects in the inner solar system has long been recognized as a necessity in order to explain the observed density variations of the terrestrial planets and the H-group, L-group dichotomy of the ordinary chondrites. This paper discusses the densities of the terrestrial planets in light of current physical and chemical models of processes in the solar nebula. It is shown that the observed density trends in the inner solar system need not be the result of special fractionation processes, and that the densities of the planets may be direct results of simultaneous application of both physical and chemical restraints on the structure of the nebula, most notably the variation of temperature with heliocentric distance. The density of Mercury is easily attributed to accretion at temperatures so high that MgSiO₃ is only partially retained but Fe metal is condensed. The densities of the other terrestrial planets are shown to be due to different degrees of retention of S, O and H as FeS, FeO and hydrous silicates produced in chemical equilibrium between condensates and solar-composition gases. It is proposed that Mercury and Venus have cores of Fe°, Earth has a core of Fe° containing substantial amounts of FeS, and Mars has a quite small core of FeS with more FeO in its mantle than in Earth’s. Geophysical and geochemical consequences of these conclusions are discussed.

The densities of the terrestrial planets can be most accurately determined by radar tracking of Mercury, Venus, and Mars, and of spacecraft in interplanetary space. The most recent estimates of the densities of the planets, by Ash et al. [1] are: Mercury, 5.42 g/cm³; Venus, 5.25; Earth, 5.51; and Mars, 3.96. Corrected to zero pressure, the densities become ~5.3, 4.40, 4.45, and ~3.85 respectively. Anderson and Kovach [2] have shown that the density may be converted into an equivalent parameter, the mean atomic weight (μ). Their method applied to the data of Ash et al. yields mean atomic weights of ~35.4, 26.6, 26.9, and 25.0, respectively, with errors of ~±0.15 at worst.

Two major theories have been proposed to account for the densities of the terrestrial planets. Urey [3] showed that, with the solar abundances of the elements then accepted, profound fractionation of metallic iron relative to silicates was required in order to effect the observed variations in density. Because of the inaccuracies in available estimates of the density of Venus, Urey was unable to conclude that Earth was in fact more dense than Venus. A very different view was that of Ringwood [4] who hypothesized that the abundances of the major rock-forming elements were the same in the various terrestrial planets, and that the density differences were caused by differences in oxidation state due to incomplete reduction of primitive Fe³⁺ to Fe° by carbon. The density of Mercury was attributed to volatilization of silicates by the Sun during its superluminous pre-main sequence phase.

My present purpose is to reassess this problem in light of the recent upward revision in the iron abundance [5–11], Cameron’s detailed physical models of the solar nebula [12], and recent progress in understanding the chemistry of solar material [14–20].

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Cameron has presented calculations on the evolution of the primitive solar nebula in which the temperature, pressure, and density profiles are computed for the early nebula [12]. The structure of the inner portions of the nebula is governed by rapid turbulence, and the temperature-pressure profile is closely adiabatic. Within the central plane of the nebula the cooling process is essentially isobaric at any given point. I will present here a subset of my results from chemical equilibrium calculations on solar material. For the present it will suffice to simplify the chemical system under consideration to H, C, O, S, Si, Mg, Ca and Fe in their solar proportions. Because there is still an uncertainty of \( \pm 20\% \) in the solar Fe:Si ratio, we will calculate the density of the condensate (as \( \rho \)) vs. \( T \) for several different acceptable values of this solar abundance ratio. Fig. 1 presents the major features of the chemistry of solar material as a general function of both temperature and pressure, and is marked with an adiabat schematically indicating the temperature-pressure profile through the nebula early in its history. Pressure can be directly related to heliocentric distance through Cameron's models, and the points of origin of the planets are indicated [12, 13]. Fig. 2 presents the density of the condensate along an isobaric section through fig. 1 at \( 10^{-3} \) bar total pres-

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**Fig. 1.** Some major features of the chemistry of solar material, 0 to 2000°K and \( 10^{-7} \) to \( 10^1 \) bar total pressure. The condensation curves of CaTiO\(_3\) (a representative refractory mineral), Fe, MgSiO\(_3\) and ice; the appearance temperatures of FeS, tremolite (a hydrous calcium silicate) and talc (a hydrous magnesium silicate); and the line at which Fe metal is wholly oxidized to FeO (as FeSiO\(_3\) and Fe\(_2\)SiO\(_4\)) are indicated. An adiabat for the nebula is drawn in, and nebular pressures corresponding to the formation conditions of the planets in Cameron's models are marked on the adiabat. The symbols, reading from the high-temperature end downward, are for Mercury, Venus, Earth, Mars, the asteroids, Jupiter, Saturn, Uranus, and Neptune. Temperatures of formation deduced from correlating the density data in fig. 2 with the observed densities of the terrestrial planets are in excellent agreement with this adiabat.

**Fig. 2.** Density of condensed material in equilibrium with a solar-composition gas, 400–1600°K at \( 10^{-3} \) bars. A simplified chemical system (the 20 most abundant elements) is employed for three different values of the Fe:Si ratio. The densities of the planets are excellently consistent with an Fe:Si ratio of 1.08, but the omission of rare elements and uncertainties in the abundances of major elements could displace the entire manifold of curves slightly. A true Fe:Si ratio below 1.0 is still possible.
sure, ranging from the condensation temperature of Fe° down to 400°K. Three different solar Fe: Si ratios are indicated. The most important features of these graphs are (1) condensation of MgSiO$_3$ near 1400°K, (2) removal of the H$_2$S from the gas by reaction with solid Fe to make FeS, and (3) oxidation of the remaining elemental iron to FeO-bearing silicates. The density of the condensate drops rapidly from that of pure iron (for which $\mu = 55.8$) during MgSiO$_3$ condensation, rises briefly by $\sim 1\%$ when FeS forms, and then drops by $\sim 5\%$ when Fe° is oxidized to FeO. Thus the density of condensed material in chemical equilibrium with the nebula shows the same general features that are observed in the densities of the planets. The striking 1% increase in the density of Earth relative to Venus is attributed to the retention of the heavy volatile element sulfur by the Earth. Since the mean atomic weight of sulfur is 32, retention of sulfur in the Earth will cause a 1% increase in $\mu$ for each 5% of sulfur content.

The correlation between the observed densities of the terrestrial planets and those predicted by the equilibrium theory is quite good. It is interesting that so good a fit can be obtained without invoking any mechanism for metal–silicate fractionation. The relative abundances of silicon, magnesium, iron, calcium, aluminum, etc. are exactly the same in Venus, Earth and Mars for this model. Mercury is seen to condense at such a high temperature that it is depleted in magnesium, silicon, and the alkali metals relative to iron, calcium, aluminum, titanium, nickel and other refractory materials. We conclude that Urey’s [3] proposal of iron-silicate fractionation involving all the terrestrial planets is an artifact of the low cosmic abundance of iron then accepted, and that metal–silicate fractionation by physical means (magnetic forces, ease of fragmentation, etc.) need not be postulated in so far as the densities of the inner planets are concerned.

Ringwood’s [4] model for producing the terrestrial planets by in situ reduction of Fe$_3$O$_4$ to Fe° by carbon involves several ad hoc hypotheses. In particular we note that Ringwood requires carbonaceous chondrite parent material, and faces the embarrassing task of removing a mass of CO from Earth roughly equal to the mass of Mars; that Ringwood postulates two separate processes to account for the densities of the terrestrial planets; that the density of Venus is explained as being less than that of Earth because of the “higher degree of oxidation of Venus”, for which no cause is suggested. Ringwood’s basic assumption that differences in oxidation state and in the degree of retention of volatiles can explain the densities of Venus, Earth and Mars is valid, but we find that, because of the high atomic weight of sulfur, density is not a monotonically decreasing function of oxidation state and volatile retention. In the present model, oxidation state and volatile retention do correlate monotonically with heliocentric distance, and the reason for this correlation is that the chemical composition of the condensate is a function of its temperature of formation.

Because of the absence of any proof that metal–silicate fractionation influences the density of the terrestrial planets, any hypothesis which requires that these planets have accumulated involatile chemical components incompletely [12], in a disequilibrium manner [4, 21], or with physical fractionation between components [3] must explain why the equilibrium theory with no fractionation does such a satisfactory job of explaining the data with far fewer arbitrary assumptions. The variation in Fe: Si ratio in the several families of chondrites is attributed to their origin in parent bodies as small as $10^{-12}$ times the mass of the Earth, in which statistical fluctuations in composition or local variations in conditions of accretion might be enormously larger than for objects of planetary mass.

The models for the terrestrial planets which emerge from the present work are as follows:

Mercury. A massive core of Fe-Ni alloy is surrounded by a small mantle of Fe°-free magnesium silicates. Ca, Al, Ti and other refractory oxides are present, but only traces of alkali metals, sulfur, FeO, etc. (due perhaps to “contamination” by infalling debris) could be present. This agrees with Ringwood’s picture of Mercury, but arises not as a result of a special additional postulate, but as an integral part of the model for formation of the planets.

Venus. A massive core of Fe-Ni alloy is surrounded by a massive mantle of Fe°-free magnesium silicates. Iron, magnesium, and silicon are present in cosmic proportions. A silica-rich crust similar in composition to Earth’s is present [22]. Sulfur is probably virtually absent from the planet [23].

Earth. An inner core of Fe-Ni alloy and outer core of Fe-FeS melt are present. Certain chalcophile el-
ments are deficient in the mantle and crust but enriched in the outer core [24–26]. These elements, which are chalcophile above the Fe-FeS eutectic temperature at oxygen fugacities typical of ordinary chondrites, may include potassium, rubidium and cesium. Earth’s mantle contains ~10% FeO. The crust and upper mantle are oxidized relative to the rest of the Earth, due to preferential enrichment of Fe$^{3+}$ in upward-flowing differentiate melt relative to solid olivine, and by the effects of the Earth surface environment. Depletion of chalcophiles in the crust and the marked deficiencies of S, K, Rb and Cs in the crust and upper mantle are due to their extraction into an FeS-rich melt. The overall composition of the Earth is rather close to that of the H-group chondrites, but is not identical to nor derived from them or any other class of meteorites.

Mars. Mars is essentially devoid of free iron. It may contain a core of FeS with or without a small amount of Fe$^{0}$ [27]. Its mantle is rich in FeO [FeO/(FeO + MgO) ~ 0.5]. Hydrous minerals were retained in appreciable quantities during accretion. The present crust (assuming differentiation has taken place and been reasonably complete) should be similar to but more iron-rich than Earth’s.

Of the terrestrial planets, only Earth is likely to have accreted at a relatively low degree of oxidation with both abundant Fe$^{0}$ and FeS present. Only Earth is likely to have differentiated so as to extract the heavy alkali metals into the core. Thus the very large heat source of $\sim 10^{20}$ erg/sec possible within the outer core of the Earth is impossible on Mercury or Venus and unlikely on Mars. The presence of a planetary magnetic dipole field on Earth and its absence on Mars is attributed to the difference in core composition.

Heat flow through the crusts of Mars, Earth, and Venus should closely approximate that predicted by the chondritic model. On Earth, deep convection of the mantle delivers heat from decay of deep-seated $^{40}$K to the base of the thin oceanic crust, and the continental crust is driven to positions over the subsiding parts of the upper mantle. The near-equality of the continental and oceanic heat flow and the close correspondence with the chondritic model are direct results of this model. In addition, the presence of the Fe-FeS eutectic melt very early in the thermal history of the Earth provides a simple explanation of early differentiation of the Earth without the necessity of postulating very rapid accretion. Because of the postulated role of an Fe-FeS eutectic melt in permitting early differentiation of the Earth, the geochemical differentiation of Earth will differ in several respects from that of the other planets. The most important distinctions are in the potassium distribution and in the time of differentiation. Venus, Earth’s near-twin, may take much longer to differentiate than Earth. In fact, Earth may differentiate before it is completely accreted, because adiabatic compression of cold material is by itself adequate to heat most of the Earth’s interior to above the Fe-FeS eutectic temperature.

Heat flow through the crust of Mercury should be higher than that calculated for a potassium-free chondritic model because we expect complete retention of U and Th relative to Fe, but less dilution by magnesio-silicates. A heat flow value close to that for a chondritic model could result from this accidental compensation.

The densities of the planets are not the only observable properties which may be strongly affected by the temperature of formation and accretion: a very interesting question is the different degree of retention of volatiles, such as H$_2$O, by the terrestrial planets. The data presented herein suggest that Earth accreted on the edge of the tremolite [Ca$_2$MgsSi$_8$O$_{22}$(OH)$_2$] stability field and Mars accreted well within it. Mars should thus contain roughly one water molecule for every two calcium atoms, or $\sim 0.3\%$ of the mass of Mars, and Earth should contain several times less water. A component of volatiles from accretion of a small proportion ($\lesssim 1\%$) of cometary or carbonaceous chondrite material cannot be ruled out [29]. In this model the primitive material present throughout the asteroid belt is of carbonaceous chondrite composition.

Further evidence for the existence of a significant radial temperature gradient and rather low temperatures in this region can be found in the densities of the satellites of Jupiter. The temperature gradient must not be substantially less than adiabatic or it becomes impossible to get accretion temperatures for the Galilean satellites low enough to explain their observed low densities [20]. The evidence from condensation models for the terrestrial planets combined with similar work on the satellites of the outer planets combine to suggest that the ordinary chondrites originated inside the orbit of Mars. The present orbits of
the ordinary chondrite parent bodies are speculative. Anders and coworkers [28, 29] have argued that the Earth and the ordinary chondrites originated at very nearly the same temperature and pressure. I would claim that this is not evidence for a great uniformity of conditions over a wide range of heliocentric distance, but rather suggests an origin for ordinary chondritic material near 1.2 AU from the Sun.

A detailed study of the chemistry of solar material is in preparation, and will be presented elsewhere.

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