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Mapping the nebular condensates and the chemical composition of the terrestrial planets

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A B S T R A C T

We demonstrate that the condensation theory of planet formation yields solids of suitable compositions in the solar nebula that accrete to form the terrestrial planetary bodies. The mineral chemistry of the condensed objects provides definite criteria to establish the pressure and temperature of their formation. The solids condensing at a high nebular pressure of 0.01 to 0.001 bar and temperature of $\sim$1530 K had the best chemical composition and density to form Mercury (64 wt% iron and 36 wt% oxides, density $\sim$5.32 g cm^3). Solids that condensed around a pressure of 0.0001 bar or less and a temperature of $\sim$700 K formed Earth and Venus (31 wt% iron, Ni and S and 69 wt% oxides, density $\sim$4 g cm^3), and Mars (33.6 wt% Fe and S and 66.4 wt% oxides, density $\sim$3.7 g cm^3). Iron sulfide provided S (3 wt%) for the core. Hydrous minerals forming in the lower temperature region provided water to the mantle. These results are highly significant because we have used only the chemical composition of the solar nebula, thermochemistry and astrophysical data on densities of the planets.

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1. Introduction

1.1. Composition of terrestrial planets

There is no reliable method to determine the chemical composition of the terrestrial planets. Our knowledge of the composition of the solar nebula is based on a combination of data from various sources, prominently the chemistry of chondrites, which dominantly consist of the silicates (pyroxene and olivine) and iron alloys. Therefore, it is not surprising that phase equilibrium calculations of the solar gas at many pressures and temperatures produce a chondritic Earth. What has been intriguing about the planetary matter is the formation of graphite, hydrous solids and oxidized minerals. This difficulty was considered as failure of the condensation theory. Graphite occurs in many meteorites/asteroids as does water and silicates with significant FeO. We decided to check all possible P and T conditions of the nebular cloud and searched those conditions where such solids would be stable. This article is about our finding of such conditions. Problems in condensation model arise when we need to explain certain details of mineralogical compositions in the chondrites and in Earth. For example, olivine (Mg, Fe)$_2$SiO$_4$ may have 10 to 20% of the iron olivine (Fe$_2$SiO$_4$) component. Such compositions cannot form in the neb-

ula at high temperatures because of the highly reducing effect of massive amount of hydrogen. Other difficulties relate to the possible formation of fluids and graphite. Thermodynamic calculation of condensing species from a cooling nebula has helped us estimate the chemical composition of terrestrial planets, asteroids and meteorites. Calculation of phase equilibrium in a gas of solar composition by Grossman (1972) led to many similar studies over the years designed to understand the origin of the planetary material that constituted the various planetary objects. Many recent studies have combined dynamical simulations of terrestrial planet formation with chemical equilibrium models of the composition of solid material (Bond et al., 2010) in the extrasolar planetary systems. Here the focus is on the use of updated thermodynamic databases in determining the pressure–temperature regimes in the nebula where terrestrial planetary materials of various compositions may form. This work is not to calculate condensation sequence of species and their sequential accumulation but instead to consider the equilibrium in different pressure and temperature regimes of the nebula, where the material of solar composition may form and accrete locally or be transported to mix with other material and form a planetary body. A judgment whether the material was transported and mixed with material forming elsewhere can be made once we have determined the equilibrium composition of the condensed material.

Lewis (1974) considered the condensation temperatures of compounds forming from the major elements in a gas of solar composition and the formation of the planets in the solar system

at various heliocentric distances. His thermodynamic calculations showed that the condensation sequence in the cooling nebula was insensitive to very widely divergent assumptions regarding the pressure variation. He examined several different temperature-pressure profiles such as the isobaric, isopynic (constant density) and isentropic adiabats and found little difference in the condensation sequence among the resulting condensates. This type of equilibrium condensation study examines the pressure–temperature space where the temperature is maintained over a period of time to allow the formation of the planetary objects (e.g. planetesimals). While it is attractive to consider that we may be able to find planetary compositions fitting pressure–temperature (P–T) spaces in the solar cloud at certain heliocentric distances, it might be more prudent to consider where in the nebula, solids of different compositions, such as graphite and hydrous minerals, may form in a cooling gas. Therefore we have mapped the density and the composition of the nebular condensates that are in equilibrium with the solar gas. We decided to study nebular condensation over a large pressure and temperature range to ensure that all P–T space is examined and compositions of the solids and gas are documented. Our calculations have succeeded in demonstrating how Earth and Mercury might have accreted in certain parts of the nebula from condensates forming locally.

1.2. Problems of condensation theory

Planetary materials e.g., planetesimals may have condensed variously in the solar gas and if accumulated homogeneously over a period may give rise to terrestrial planets at suitable heliocentric distances; this was the assumption which Lewis (1974) used. This theory did not explain the mass distribution of the terrestrial planets, as Mercury and Mars have smaller masses. Mercury's smaller mass has been as due to stripping of the mantle leaving a large iron core behind. It should be possible to fit the size and density of Mars to its formation at a heliocentric distance beyond Earth.

Problems of the condensation theory of planet formation have been discussed amply (Lewis, 1974; Fedkin and Grossman, 2004, 2006; Grossman et al., 2011, 2012) and one of these is the highly reducing state of the nebular gas not permitting the formation of fayalite rich olivine at high temperatures. Huss et al. (2006) found that the mean fayalite content of olivine grains in the matrices of primitive ordinary chondrites ranges from 25 to 50 mole% of fayalite. According to Brearley and Jones (1998), the average mole fraction of fayalite in olivine is 0.05–0.10 in CI and CM chondrites, ~0.07, in chondrules of CV chondrites, 0.38 in R chondrites, ~0.50 in the matrices of CO and CV chondrites. Rietmeijer (1998) reported fayalite content of 10% in interplanetary dust particles. Palme and Fegley (1990) discussed the high temperature condensation problem of iron rich olivine Earth's mantle consists of olivine with 8 to 15% of fayalite. The failure to account for such iron oxide enrichment is considered a significant setback for the condensation theory of planet formation.

1.3. Kinetic consideration

These are equilibrium calculations and provide reference states for various reactions that may not be completed or inhibited due to kinetics. Thus Lodders (2003) argues that the C–H–O equilibrium may be affected by the fact that the slow rate of the reaction

$$CO + 3 H_2 = CH_4 + H_2O$$

may affect the availability of water to other reactions. Fig. 1 shows the water availability if enough time is allowed in the condensation sequence for the reaction of CO with hydrogen to water and methane. The hydrous phase in equilibrium calculations does
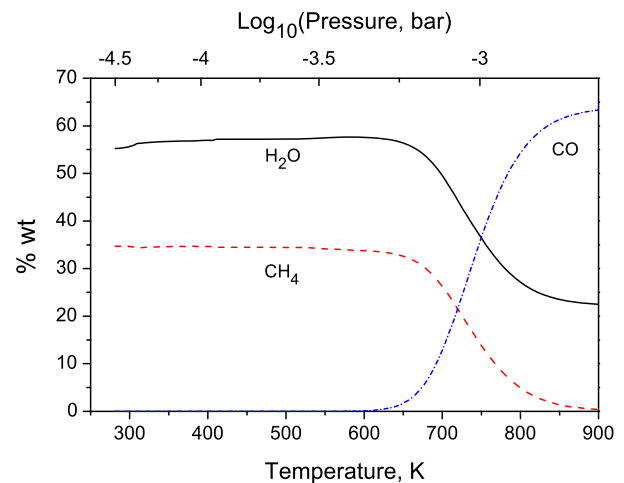

Fig. 1. Lodders (2003) suggested that the reduction of CO to CH_4 with decreasing temperature is one of the key reactions that affects availability of H_2O. The figure shows the water availability as a function of temperature.

not appear until the temperature has reached below 450 K. The equilibrium condensation model cannot provide us with any more information if the time in cooling from 800 K to 400 K will be enough for the reaction to proceed and produce significant amount of water available to form hydrous phases.

2. The model

2.1. System composition and the thermodynamic database

Over the years, there has been significant progress in the availability of thermochemical and physical property data of solids. Databases that contain internally consistent data in many multicomponent systems are now available e.g. for the oxides by Fabrichnaya et al. (2004). An internally consistent database is obtained by using the CALPHAD method (Bale et al., 2002) which requires the comparison of the experimentally determined phase diagram with the equilibrium reaction curves calculated using thermochemistry. The internal consistence is achieved when the optimized data produces the experimental phase diagram within permissible errors.

The major element composition of the solar gas according to Anders and Ebihara (1982) is (moles when Si is 1) Si 1.0, Al 0.0849, Mg 1.075, Fe 0.9, C 12.1, H 27 200, O 20.1, Ca 0.0611, Na 0.057, K 0.00377, S 0.515, N_2 0.48, Ti 0.0024, Ni 0.0493. Other estimates by Cameron and Pine (1973) are not significantly different. However the recent review of the abundance data by Lodders (2003) led to the following abundances of the elements Si 1.0, Al 0.0841, Mg 1.02, Fe 0.838, C 7.079, H 28 840, O 14.13, Ca 0.0683, Na 0.0575, K 0.00369, S 0.4449, N_2 0.48, Ti 0.0024, Ni 0.0478. We have adopted Lodders' recommended data for our calculation.

Although no single database is available that includes all the phases in this 14-element system, data on oxides FeO–MgO–Al_2O_3–SiO_2 (Fabrichnaya et al., 2004) that is consistent with experimental phase diagrams can be relied on. This oxide database has been extended by us to include CaO, Na_2O and K_2O and it is closely similar to the separately organized metallurgical databases such as the SGTE database and the oxide database in the FACTSAGE databases (Bale et al., 2002). The total number of solids is in excess of 650 and the gas species used are 220.

An important aspect of the database is the use of appropriate solid solution models. For multicomponent multisite solid solutions, we have used the sublattice or compound-energy model of Hillert et al. (1997) for silicates. The details may be found in Fabrichnaya et al. (2004) and in Bale et al. (2002).