CHEMISTRY OF THE SOLAR NEBULA  
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ABSTRACT. The solar system is believed to have formed from a primordial gas and dust cloud, i.e., the primitive solar nebula (PSN). Constraints on the chemical composition and structure of the PSN are provided by observed densities and compositions of the planets, the asteroids and meteorites together with theoretical modelling. Many of these properties can be explained by equilibrium condensation from a solar composition gas. Other observations suggest that this model is too simple and additional processes, such as kinetic inhibition, heterogeneous accumulation, and volatile element transport must be considered.

1. INTRODUCTION

The sun, its planets, satellites, asteroids, and comets were created from a primordial gas and dust cloud commonly referred to as the primitive solar nebula (PSN). It is estimated that about 98% of the total mass of the PSN was a mixture of hydrogen and helium, slightly less than 2% was ice-forming materials, and about 0.5% was rock-forming solids. Elemental abundances for the PSN, the solar-system abundances, are inferred from meteorite and solar atmosphere compositions (see the recent review by Anders and Grevesse, 1989).

2. FORMATION AND STRUCTURE OF THE PSN

The solar system began as part of a dense interstellar gas and dust cloud. This interstellar cloud was compressed by some means, such as a passing shock wave from a stellar explosion or the radiation pressure of surrounding stars. The cloud became sufficiently dense for its gravitational potential energy to exceed its internal thermal energy, and began to collapse. The collapsing interstellar cloud's angular momentum caused fragmentation into dense cloudlets orbiting about a common center of mass. One of these cloudlets eventually became the PSN. This cloud continued to collapse by radiating off internal energy, and lost angular momentum by shedding mass from its outer edges and by further fragmentation.

As the PSN collapsed, conservation of angular momentum resulted in an increase of angular velocity. This spin-up inhibited further collapse toward the rotation axis, and the nebula collapsed parallel to
the spin axis into a flattened, symmetrical, disklike shape. Material located in the inner part of the nebula heated up sufficiently to vaporize solids; farther out the heating was less, and dust grains inherited from the interstellar cloud survived. The disk was initially cooled by convection, and temperature decreased linearly with distance from the center of the nebula, following an adiabatic gradient. As temperatures decreased in the PSN, particles condensed. These particles were concentrated by gas drag in a thin layer in the center of the nebula, and began to agglomerate into larger objects.

At some point, temperatures and pressures in the center of the nebula became high enough that nuclear reactions could occur and the central star began its presumed T-Tauri phase. The young star was extremely luminous and emitted a stream of protons and electrons a million times stronger than our sun's present solar wind. Any gas and unaccreted dust was rapidly swept from the solar system; the PSN ceased to exist. Radiative transport replaced convective transport of heat. Temperatures no longer decreased linearly with distance, but rather as \( r^{-1/2} \). Material in the inner solar system cooled when the nebular gas was removed, while material in the outer solar system heated up. Solid material continued to accrete, and the moons and planets formed.

3. CHEMICAL PROCESSES IN THE PSN

3.1 Equilibrium Condensation

The simplest model for the chemical processes that occurred in the PSN is that of equilibrium condensation. This model calculates the major element composition, mineralogy, and volatile element content of unaccreted solids in the PSN by chemical equilibrium methods as functions of temperature and pressure. Intimate contact between gas and condensed solids is required for strict thermodynamic equilibrium to be maintained.

The results of the equilibrium condensation model are path-independent. It is impossible to determine whether the presently observable chemical state was reached by heating or cooling. Although it is convenient to think in terms of a condensation sequence beginning at very high temperatures, it is neither certain or even likely that solid solar system materials were fully vaporized in the PSN. It is more likely that the condensation temperatures of solids in the PSN were actually equilibrium temperatures, reflecting the highest temperature at which gases and solids were intimately mixed.

Equilibrium condensation models have been used as tools to explain the varied mineralogies, oxidation states, and volatile element contents of the chondritic meteorites (e.g., Lord, 1965; Larimer, 1967; Larimer and Anders, 1967, 1970; Grossman, 1972, 1973; Grossman and Larimer, 1974). Major-element condensation calculations have also been used to interpret the available data on the compositions and structure of the planets, and on the chemical and isotopic compositions of planetary and satellite atmospheres (e.g., Lewis, 1972a,b, 1973a,b, 1974a,b; Barshay and Lewis, 1975, 1976, 1978; Fegley and Lewis, 1979, 1980). The results