

**A THEORETICAL CONSIDERATION ON THE CHEMICAL  
COMPOSITION OF IMPACT-INDUCED ATMOSPHERES ON MARS,  
EARTH, AND SUPER-EARTHS**

by

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## ABSTRACT

The composition of impact-induced atmospheres controls planetary climatic conditions during and immediately after accretion. Impact-induced atmospheres would occur on terrestrial planets immediately after their accretion and perhaps during the so-called late heavy bombardment (LHB) period in the solar system. Planetary atmospheres during such early evolution stages are particularly important for Earth and Mars, because Earth may have been experienced life's origin and Mars may have maintained warm and wet climate despite the young faint Sun paradox during this period. The approaches taken by previous studies on impact-generated atmospheres, however, may not have been accurate; they estimate the composition of impact-induced vapor with equilibrium calculation as a function of temperature under constant pressures. This approach is appropriate if chemical reaction in impact-induced vapor is controlled by radiative cooling because radiative cooling decreases temperature while pressure is kept approximately constant. In reality, impact-induced vapor adiabatically expands; both pressure and temperature changes simultaneously. Such behaviors cannot be considered readily in the framework of these previous studies

Entropy gain during the shock-compression phase controls the temperature-pressure pathway of the decompression phase. Also, terminal temperature or pressure where chemical reactions stop (i.e., quenching) is important. In other words, the initial conditions due to impact heating and when quenching occurs determine the chemical compositions of adiabatically expanding impact-induced vapor. Thus, estimation of the initial entropy gain and subsequent quenching are the key for accurate estimation of the chemical composition of impact-generated atmospheres. The goal of this study is to model chemistry within adiabatically expanding impact-induced vapor in this framework, and investigate how different the chemical composition of impact generated atmospheres among terrestrial planets and super-Earths is.

Thermodynamically stable chemical compositions depend on temperature, pressure, and elemental compositions. Thus, constraints on these values are required for modeling chemical compositions of impact-generated terrestrial atmospheres. In this study, we assume CI chondrites as the impactor that mainly contributes volatiles to terrestrial planets during the terminal phase of planetary accretion and LHB. To determine the temperature-pressure paths of adiabatically expanding impact-induced vapor, we estimate the entropy gain during the shock-compression phase of chondrites using the Hugoniot equation of state for silica.

The calculation results show that the redox disproportionation of carbon occurs at

lower entropy states achieved by low velocity impacts (i.e.,  $\leq 13$  km/s). For low-velocity impact-induced vapor (i.e.,  $\leq 13$  km/s),  $\text{CH}_4$  can be thermodynamically stable even at high quench temperatures (i.e.,  $\sim 1500$  K) due to high pressure effects. We also found that the transition temperature of the vapor having the entropy of  $6.0$  kJ/K/kg achieved by high velocity impacts (i.e.,  $\geq 23$  km/s) (i.e.,  $1700$ - $2700$  K) is higher than that of the vapor having the entropy of  $4.0$  kJ/K/kg achieved by low velocity impacts (i.e.,  $\leq 13$  km/s) (i.e.,  $500$ - $1000$  K). Consequently, radiative cooling may be more important for determining impact-induced atmospheres in the case of a massive planet or planets with high impact velocities, such as super-Earths and Earth during LHB. In contrast, for smaller mass planets or planets with low impact velocities, such as Mars and accreting Earth, adiabatic cooling may become more important.

These calculation results strongly suggest that the chemical compositions of impact-induced atmospheres among terrestrial planets may be strongly different even if the composition of accreting material were same, suggesting that early Mars and early Earth may have undergone different chemical evolutions.