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Chemical composition diversity among impact-generated atmospheres on terrestrial planets: The effect of impact velocity

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Prebiotic chemistry and climate conditions of early Earth and/or Mars would have been suitable for origin and evolution of life. The chemical composition of atmospheres during early evolution stages is important for understanding these factors.

Impact-generated atmospheres would occur on terrestrial planets immediately after their accretion and perhaps during the late heavy bombardment (LHB) period in the solar system. 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 [e.g., 1, 2]. 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; nevertheless such behaviors have not been considered. Entropy gain during the shock-compression phase controls the temperature-pressure pathway of the decompression phase. 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, and investigate how sensitively impact-generated atmospheres depend on impact velocity.

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 heavy bombardment [e.g., 3]. To determine the temperature-pressure paths of adiabatically expanding vapor, we estimate the entropy gain during the shock-compression phase using the Hugoniot equation of state for silica [4]. Then, we calculate the major composition of a gas and condensed phase along isentropic lines within a range of pressures (0.01-10000 bars) and temperatures (500-2500 K). The model calculations are performed using a Gibbs free energy minimization code [5]. Elements included in our calculations are H, C, O, N, S, Mg, Al, Si, Fe. Elemental abundances used in our calculations are taken from [6].

Our calculation results show that the redox disproportionation of carbon occurs at low entropy states achieved by low-velocity impacts ($<$13km/s). For high-velocity impact ($>$17km/s), impact-induced vapor is rich in diatomic molecules, such as CO and H_2. For low-velocity impact-induced vapor ($<$13km/s), CH_4 becomes thermodynamically stable even at high quenching temperatures ($>$1000K). This is because the adiabatic curve for low entropy states undergoes higher pressures at a given temperature. High pressure is thermodynamically favorable for the formation of polyatomic molecules, such as CH_4 and NH_3; i.e., Le Chatelier' s principle. These calculation results strongly suggest that the chemical compositions of impact-generated atmospheres among terrestrial planets may be different even if the composition of accreting material were same, suggesting that early Mars and early Earth may have possessed a CH_4-rich reducing atmosphere and a CO- and CO_2-rich more oxidizing atmosphere, respectively.

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