INTERACTION BETWEEN IMPACT VAPOR CLOUDS AND THE EARLY MARTIAN ATMOSPHERE.
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Introduction: Interactions between impact-induced vapor clouds and the ambient planetary atmospheres are considered to have played a very important role in the evolution of planetary atmospheres and surface geology. However, the detailed analysis of such interaction has not been studied extensively before. In this study, we attempt to construct a simple model of vapor-atmosphere interactions taking into account the effects of both fluid dynamics and chemical reactions.

Mars: Whether or not Mars had a warm and wet climate is one of the most controversial issues in Mars science. If a large amount of methane existed in the Mars atmosphere, it may be able to warm Mars to temperatures above freezing [1]. However, it is not known if there was a process that can supply methane at high rate enough to withstand the rapid destruction by UV-induced photochemistry. Because fluvial features on Mars appear to be contemporaneous to the late-stage heavy bombardment [4], the possible warm climate may have been maintained by impact-related processes.

Impact Scenarios: A number of impact-induced mechanisms have been proposed to produce a large amount of CH₄. For example, atmospheric re-entry process of vapor condensates from a large iron-rich impact has been proposed to induce Fischer-Tropsch reaction and produce CH₄ globally [5]. This process, however, requires a relatively high concentration of preexisting H₂ in the atmosphere. Thus, although it is probably very effective for a few hundred million years after the planetary accretion, it may not be very effective near the end of the late-stage heavy bombardment period.

Fischer-Tropsch reaction within vapor plumes due to cometary impacts has also been proposed to produce a large amount of CH₄ [6]. This model, however, assumes that dust condensates from cometary vapor have the same catalytic efficiency as industrial catalysts with metallic iron and nickel on the grain surfaces. Equilibrium calculations indicate that iron and nickel in cometary composition vapor are likely to condense as FeO and Ni₂S₃, whose catalytic efficiencies are much lower than metals. Furthermore, high-temperature impact vapor plumes are likely to be lifted quickly by buoyancy force [7,8]. This uprise will lead to intense entrainment of ambient air, analogously to volcanic eruption plumes [8]. If the ambient atmosphere is dominated by CO₂, oxygen fugacity within the uprising vapor plume will greatly increase. This may reduce methane productivity greatly. Thus, cometary impacts may not be very efficient in delivering methane to a planet with a CO₂-dominated atmosphere.

New Process: In this study, we propose a methane-producing mechanism that does not require a reducing atmosphere or efficient catalytic properties of metal oxides or sulfides considering both fluid mechanical and chemical interaction between impact vapor clouds and the ambient atmosphere. More specifically, we consider impacts of iron meteorites into H₂O (e.g., ocean, polar cap, or permafrost) under a CO₂-dominated atmosphere, taking account of oxidation of meteoritic matter, atmospheric entrainment due to buoyancy uprise, and Fischer-Tropsch reaction on the surface of survived meteoritic metals.

Impact Vaporization and Condensation: A simple analytical calculation using the Gamma model [9] indicate that the amount of vaporized water is larger than iron impactor mass if the H₂O layer is thicker than 1/15 – 1/20 the projectile diameter. If this condition is
met, the resulting vapor will have an approximately constant yield of H₂ after the adiabatic.

Figure 2 shows the equilibrium chemical composition of Fe-Ni-H₂O mixture as a function of temperature, depicting the condensation sequence within a vapor plume due to an iron meteorite impacting H₂O. Unlike in cometary vapor, nickel condenses as metal in this vapor plume, although iron condenses as oxide. Here, it is noted that metallic nickel condenses after iron oxide condenses, allowing metallic nickel exposed to the gas phase after adiabatic cooling.

Buoyancy Uprise Process: After adiabatic decompression, entrainment of cold ambient air becomes the dominant cooling process of an impact vapor plume. The temperature T of the air-vapor mixture is given by a simple heat balance between hot vapor and entrained cold air. Calculation results indicate that plume temperature goes through the catalytically active range when 1 to 10 times the vapor mass of air is entrained, depending on the post-decompression vapor temperature. This will require > (2L/g)²/2 of time (~10⁷ seconds for 10 km of vapor plume [8]), where L and g are plume diameter and gravity, respectively. This time scale is comparable to the time needed for industrial catalyst to convert H₂ to CH₄ within a vapor cloud [6]. Because vapor condensates expected in the vapor plumes considered in this study are small iron oxide grains coated with metallic nickel layer, it is very similar to industrially utilized catalysts. Thus the duration of catalytically active temperature condition is likely to be long enough to convert H₂ to CH₄.

Then near-equilibrium concentration of CH₄ can be catalytically produced in an uprising vapor cloud. Figure 3 shows the equilibrium yield of methane from uprising impact vapor plumes. Calculation result shows that methane yield reaches higher than 1/3 the stoichiometric maximum (i.e., 1/4 mole of CH₄ for 1 mole of initial H₂) within the catalytically active temperature range (400 – 600 K) when vapor mixing ratio is >10%. Such high vapor mixing ratios at catalytically active temperatures is achieved when post-decompression vapor temperature is lower than ~2000 K (Figure 3). Because the above Gamma-model calculation indicates that mean pre-decompression vapor temperature for iron meteorites at 10 km/s is 1800 – 2400 K, this condition can be met by a large fraction of iron impactors.

Warm Paleo-Mars? When a 30 km of iron meteorite hit a H₂O ice body, it would produce 0.2% of CH₄ in a 2 bar of CO₂ atmosphere on paleo-Mars. This composition of atmosphere is estimated to warm Mars to temperatures above freezing [1]. Although such a large impact is not expected to occur frequently, it must have occurred at least several times during the heavy bombardment period. Then, a warm climate may have occurred episodically and last for several hundred of years of time (i.e., the photochemical lifetime of methane [10,11]). Such episodic occurrence of warm climate is consistent with geologic record of Mars [12].