AN EFFICIENT METHANE PRODUCING MECHANISM DUE TO IRON METEORITE IMPACTS.

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Summary: Whether or not paleo-Mars had a warm and wet climate is one of the most controversial issues in planetary science. If a large amount of methane existed, Mars may have been kept warm due to its strong greenhouse effect. In this study, we propose a mechanism to produce a large amount of methane from iron meteorites impacting H_2O under a CO_2-rich atmosphere.

Introduction: Although a large amount of methane may be able to warm Mars to temperatures above freezing [1], 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.

In fact, a number of impact-induced mechanisms have been proposed to produce a large amount of CH_4. For example, atmospheric re-entry process of vapor condensates from a large iron-rich impact has been proposed to induce Fischer-Tropsh reaction and produce CH_4 globally [5]. This process, however, requires a relatively high concentration of preexisting H_2 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-Tropsh reaction within vapor plumes due to cometary impacts has also been proposed to produce a large amount of CH_4 [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 comet-composition vapor are likely to condense as FeO and Ni_2S_3, 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 leads to intense entrainment of ambient air, analogously to volcanic eruption plumes [8]. If the ambient atmosphere is dominated by CO_2, 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 CO_2-dominated atmosphere.

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. More specifically, we consider impacts of iron meteorites into H_2O (e.g., ocean, polar cap, or permafrost) under a CO_2-dominated atmosphere, taking account of oxidation of meteoritic matter, atmospheric entrainment due to buoyancy uprise, and Fischer-Tropsh reaction on the surface of survived meteoritic metals.

Impact Vaporization and Condensation: When the thickness of target H_2O layer is much larger than the diameter of an impacting body, the vaporized water mass can be estimated with the Gamma model [9]. A typical impact velocity of 10 km/s on Mars will result in vaporized water mass 1.9 – 2.7 times the iron impactor mass. This corresponds to 5.9 – 8.9 of molar ratio of H_2O/Fe in the resulting vapor cloud. Here, we consider near-vertical impacts and assume that both projectile vapor and target vapor are mixed well rapidly. If half of the impact energy (10 MJ/kg) is partitioned to the internal energy of the vapor cloud, the mean vapor temperature is ~1800K before decompression. If the target contains 50% of silicate, the temperature will be ~2400K. As the vapor decompresses, the temperature will decrease, and solid and liquid phases will appear.

Figure 1 shows the equilibrium chemical composition of Fe-Ni-H_2O mixture as a function of temperature, depicting the condensation sequence within a vapor plume due to an iron meteorite impacting H_2O. 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. Another important result is that 1 mole of H_2 is generated for 1 mole of Fe metal in the impactor. This does not depend of the molar ratio between iron and vaporized H_2O, warranting a high abundance of H_2 in a post-decompression vapor plume.

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. Figure 2 shows 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 $> (2L/g)^{1/2}$ of time (~10^2 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 H_2 to CH_4 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 H_2 to CH_4.

Then near-equilibrium concentration of CH_4 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 CH_4 for 1 mole of initial H_2) 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 2). 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.

Methane Yield: When 50% of CH_4 yield is used, 10 ppb of CH_4 in the present 6mb Martian atmosphere [10,11] requires an iron meteorite about 80 m in diameter impacting a polar cap, leaving a crater with diameter on the order of 1 km.

Similarly, a 30 km of iron meteorite is required to produce 0.2% of CH_4 in a 2 bar of CO_2 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 occur 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].

Although the assessment conducted in this study needs more detailed calculations before a decisive conclusion can be drawn, the preliminary results are promising and show that this process deserves further investigation.

References: [1] Kasting, J.F (2002) *AGU Fall Meeting, #P51B-0345*. [4] Carr, M.H. (1981) *The Surface of Mars*, Yale Univ. Press, New Heaven. [5] Sekine, Y. et al. (2003) *JGR, 108*, 10.1029/2002JE002034. [6] Kress M. and C.P. McKay (2004) *Icarus, 168*, 475-483. [7] Jones E. and J.W. Kodis (1982) *GSA Sp. Pap., 190*, 175-186. [8] Suigta, S. and P.H. Schultz (2002) *Icarus, 155*, 265-284 [9] Croft, S.K. (1982) *GSA Sp. Pap., 190*, 143-152. [10] Formisano, V. et al. (2004) *Science, 306*, 1758-1761. [11] Krasnopolsky, V.A. et al. (2004) *Icarus, 172*, 537-547. [12] Schultz, P.H., (1987) *Kagaku, 67*, 486-495.
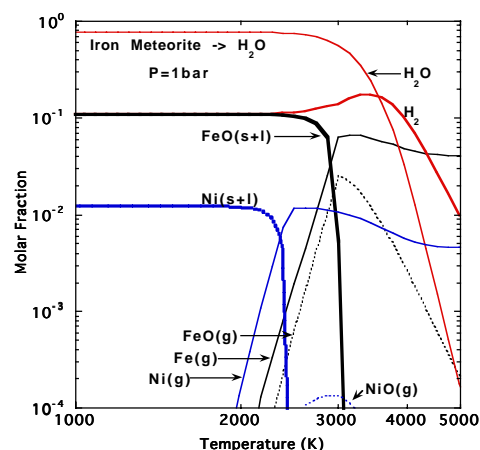

Figure 1. Equilibrium chemical composition of vapor plumes due to iron meteorites impacting H_2O target as a function of temperature at 1bar. The molar mixing ratio in the vapor is assumed to be H_2O:Fe:Ni=1:0.13:0.14.
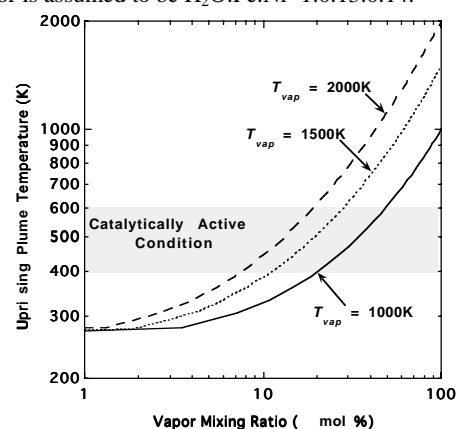

Figure 2. Temperature in buoyantly uprising vapor plume as a function of vapor mixing ratio. T_{vap} shown in the figure indicates the post-decompression temperature of vapor plume before air entrainment due to uprise. The temperature range where Fisher-Tropsh catalytic reaction is active is also shown.
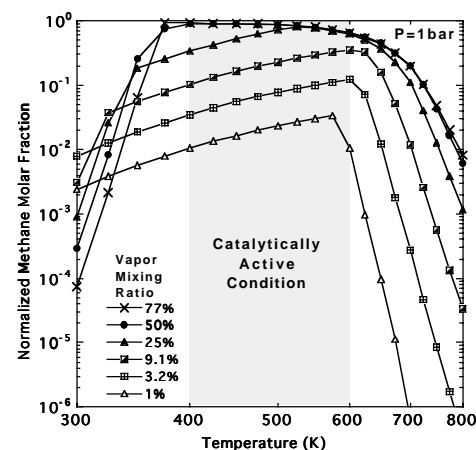

Figure 3. Equilibrium methane yield normalized by the stoichiometric maximum methane yield (i.e., 1/4 of initial H_2) within an impact vapor plumes uprising through a CO_2 atmosphere as a function of temperature and mixing ratio of H_2-rich impact vapor at 1 bar.