THICKNESS OF MARTIAN GROUND ICE: IMPLICATION FROM MULTI-WATER-RESERVOIR MODEL

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Introduction: Martian surface ice is currently observed only as polar layered deposits (PLDs), whereas Mars Odyssey Gamma Ray Spectrometer [1,2] and Mars Express's radar sounder observations [3] propose the presence of much larger amount of ground ice in the mid- to high-latidutes. Such a ground-ice region is expected to spread over a few tenths of percent of the total Martian surface, yet the thickness (i.e. volume) is poorly constrained [3].

The thickness of the ground ice is related to the evolution history of the Martian water reservoirs. After ancient oceans became extinct, the oceanic water would become "surface ice", which currently occurs as PLDs, and "ground ice" which would extend from high latitude to mid- or low-latitude. Atmospheric escape of hydrogen and oxygen through the Martian history causes decrease of the amount of the ice. The signature of the evolution history is recorded by hydrogen isotope ratio (D/H). Martin atmosphere and soil have D/H ratio of ~ 6 (relative to SMOW) [4,5], which is distinctly higher than the Martian primitive D/H ratio of ~ 1.3 [6]. The escape rate is estimated by using the D/H ratio and the amount of PLDs, which is relatively well constrained [7,8]. Then the amount of the ground ice can be constrained by the estimated escape rate and the D/H ratio. This study constrains the thickness of the ground ice by using an evolution model of D/H ratio of multi-water-reservoirs during the ice age.

Model: Our model is based on a multi-water-reservoir box model of [9]. We assume two different water-reservoir: surface ice and ground ice (Fig. 1). Their hydrogen isotope compositions evolve due to atmospheric escape, exchange between ice and water vapor (sublimation), and atmospheric mixing. Assuming the thickness of the ground ice (expressed by mean thickness of pure ice), the current D/H ratio after 4 Gyr is obtained as a result.

The areal extent of the surface ice is given by that of the current PLDs. The ground ice is expected to have a larger surface area than the surface ice. We assume the areal extent of the ground ice comparable to that of Noachian Arabia ocean (~ one-fourth of the total Martian surface [10]). The young age of PLDs (0.5-2 Ma) [11] suggests that the surface ice is actively exchanged with atmosphere. On the other hand, the activity of the ground ice is unknown. We propose two models: Model A assumes that the whole ground ice is exchanged with atmosphere, while Model B assumes that only thin active layer near surface having a constant thickness through time is exchanged with atmosphere (Fig. 1).

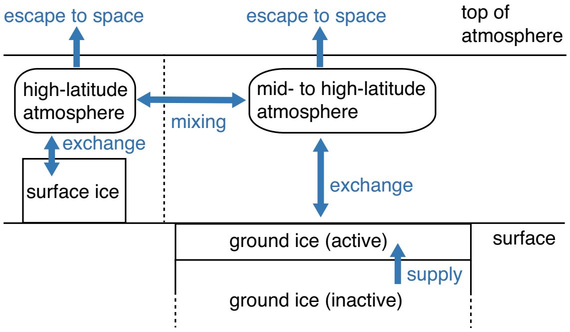

Figure 1: Schematic illustration of the two-reservoir model for the evolution of the water reservoir on Mars. Inactive ground ice is assumed only in Model B.

The D/H ratio fractionates due to atmospheric escape and sublimation. We assume the D/H fractionation coefficient for atmospheric escape R = 0.15. The escape rate linearly decreases from 600 times the present value to the present value, which is estimated to fractionate the D/H ratio of the surface ice to ~ 6. We assume the D/H fractionation coefficient that applies to the phase change that brings the vapor into or onto the ice $\alpha = 1.35$ [12]. The initial D/H ratio is that of ancient ocean, which is informed by D/H data of the Martian meteorite ALH84001 formed at ~ 4.1 Ga [13]: $(D/H)/(D/H)_{SMOW}$ ~ 2.2-4.0 [14,15], we assume the D/H ratio of 2.0 for the initial condition.

We follow the fiducial model of [9] for the other model parameters. Mixing timescale of atmosphere is ~ 10^3 years ($f_m = 2.5$ in the parameterization of [9]). The effect of obliquity cycle is moderately included ("MEDIUM" case in the parameterization of [9]).

Results: Evolution of D/H ratio in both Model A and Model B is shown in Fig. 2. Thinner ice results in higher D/H ratio. Because the same amount of ice is lost due to atmospheric escape (thickness of ~ 1800 m), thinner current thickness is more fractionated. Obtained D/H ratio of ground ice after 4 Gyr in both Model A and Model B is shown in Fig. 3, as a function of the current thickness. In Model A, the initial thickness of ~ 2300 m is required to produce a D/H ratio of ~ 6. Pure ice is assumed in our model, but actual ground ice would be a mixture of ice and rock. The required thickness is a few times larger than our model

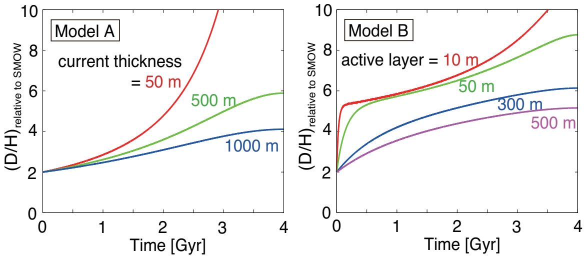

Figure 2: Evolution of D/H ratio of ground ice relative to SMOW. The lines are results for the different initial thickness in Model A and for the different thickness of active layer in Model B.

value because volumetric fraction of ice would be several tens of percent [3]. It might be hard to uniform D/H ratio of such a thick ice layer. Thus Model B, in which only thin active layer can exchange for atmosphere, would be preferred. The D/H ratio in Model B is suppressed compared to Model A (Figs. 2 and 3). In Model B, thickness of ~ 300 m is required to produce a D/H ratio of ~ 6 for the active layer. As inactive ice layer which conserves lower D/H ratio is required below the active layer, the estimated thickness of the active layer is a minimum estimate of the thickness of the ground ice.

After an early growth, change of D/H ratio is suppressed in Model B (Fig. 2). Thin active ice results in a concentration of deuterium in the ice layer and atmosphere. Even with an small fractionation factor of R = 0.15, which contributes to an effective fractionation, atmospheric deuterium starts to escape because of the concentration. As a result, the fractionation due to the atmospheric escape becomes ineffective in Model B, which causes the lower D/H ratio in Model B (Fig. 3).

Discussion: This study suggests that inactive ice layer having lower D/H is conserved below active ice layer. Recently [16] reported that impact melts in Martian meteorites contain a contribution from an unknown reservoir having a lower D/H ratio of ~ 2.5-3.0. The unknown reservoir might be the inactive ground ice conserved in subsurface as shown by our calculation.

The active ground ice whose thickness is ~ 300 m is required to produce D/H ratio of ~ 6. Diffusion of HDO in ice reach only ~ 10 m within ~ 1 Gyr (assuming the molecular diffusivity of 10^{-14} m^2 s^{-1} [17]. Nature of this active ground ice might be partially melted ice, hydrated clathrates in underground cryosphere, or breathing porous permafrosts [18]. Actual thickness of the ice depends on porosity and filling fraction. Recent observations have found recurring slope lineae in widespread regions on Mars [19], suggesting melting of the ground ice. Partial melting is a possible mechanism to activate the ground ice.

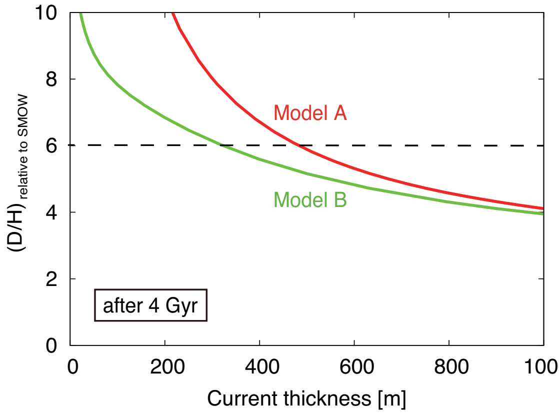

Figure 3: D/H ratio of ground ice relative to SMOW as a function of current thickness after 4 Gyr. The shown is the thickness of ground ice for Model A but is the thickness of active layer only for Model B.

Our model assumes the present configuration of water reservoirs; surface ice exists in smaller polar regions compared to widespread ground ice. The assumption calls for an larger escape rate per area such that the D/H ratio of the surface ice fractionate from ~ 2 to ~ 6. The young age (0.5-2 Ma) [11] of PLDs implies that the present configuration of the surface ice might be a transient state. If surface ice has been widespread as the typical state through time, the required escape rate is lower and the thickness of the active ground ice having high D/H might be thinner.

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