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Impact-driven planetary desiccation: The origin of the dry Venus

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ABSTRACT

The fate of surface water on Venus is one of the most important outstanding problems in comparative planetology. Although Venus should have had a large amount of surface water (like the Earth) during its formation, the current water content on the Venusian surface is only 1 part in 100 000 of that of the mass of Earth's oceans. Here a new concept is proposed to explain water removal on a steam-covered proto Venus, referred to as "impact-driven planetary desiccation". Since a steam atmosphere is photochemically unstable, water vapor dissociates into hydrogen and oxygen. Then, hydrogen escapes easily into space through hydrodynamic escape driven by strong extreme ultraviolet radiation from the young Sun. The focus is on the intense impact bombardment during the terminal stage of planetary accretion as generators of a significant amount of reducing agent. The fine-grained ejecta remove the residual oxygen, the counter part of escaped hydrogen, via the oxidation of iron-bearing rocks in a hot atmosphere. Thus, hypervelocity impacts cause net desiccation of the planetary surface. I constructed a stochastic cratering model using a Monte Carlo approach to investigate the cumulative mass of nonoxidized, ejected rocks due to the intense impact bombardment. The ejecta mass after each impact was calculated using the π-group scaling laws and a modified Maxwell's Z model. The effect of projectile penetration into the ground on the ejecta mass was also included. Next, an upper limit on the total amount of removed water was calculated using the stoichiometric limit of the oxidation of basaltic rocks, taking into account the effect of fast H_2 escape. It is shown that a thick steam atmosphere with a mass equivalent to that of the terrestrial oceans would be removed. The cumulative mass of rocky ejecta released into the atmosphere reaches 1 wt% of the host planet, which is 10 000 times of the current mass of the Earth's atmosphere. These results strongly suggest that chemical reactions between such large amounts of ejecta and planetary atmospheres are among the key factors required to understand atmospheric mass and its composition, not only in the Solar System but also in extrasolar systems.

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1. Introduction

The reason for the lack of moisture on Venus (e.g., Donahue et al., 1982) has been a long-standing problem in the context of understanding how habitable planets are formed. Since Venus is Earth's twin, it would have been formed with a similar amount of surface water to that of Earth's ocean (e.g., Matsui and Abe, 1986). The total amount of surface water on planets is one of the most important parameters required to determine the evolution of the surface environment on terrestrial planets. This is because water largely controls geodynamical and geochemical processes owing to its strong greenhouse effect in the gas phase and its nature as a strong solvent in the liquid phase. In addition, water largely affects the rheological properties of rocks (e.g., Korenaga and Karato, 2008). The mechanism responsible for causing a water deficit on the Venusian surface must be explored to understand the origin of the significant difference in the surface environment between Earth and Venus.

Previous studies proposed that the problem of water removal from Venus comes down to the fate of oxygen generated by extreme ultra violet (EUV) because of the following reasons. Water vapor might be dissociated into hydrogen and oxygen by the much stronger EUV radiation from the young Sun (e.g., Kasting and Pollack, 1983) compared with that at the present time. Hydrogen can easily escape into space through EUV-driven hydrodynamic escape (e.g., Kasting and Pollack, 1983; Zahnle and Kasting, 1986; Sasaki, 2008). The Pioneer probe showed that the ratio of deuterium to hydrogen (D/H) in the current Venusian atmosphere is enriched by a factor of 120 ± 40 (de Bergh et al., 1991). Such high D/H ratio is thought to be an evidence of the hydrogen escape to the space (e.g., Kasting and Pollack, 1983). In the context of the dissociation of water vapor into hydrogen and oxygen, previous studies have investigated the fate of oxygen based three processes: (1) frictional

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escape caused by drag-off by the escaping hydrogen flow (e.g., Chassefière, 1996; Gillmann et al., 2009; Kasting and Pollack, 1983; Sasaki, 2008; Zahnle and Kasting, 1986), (2) nonthermal escape by ion pick-up owing to the solar wind (e.g., Kulikov et al., 2007; Terada et al., 2009) and (3) oxidation of the Venusian surface (e.g., Hamano et al., 2013; Gillmann et al., 2009; Lewis and Prinn, 1984).

The first and second processes are considered equivalent to the escape of oxygen into space. A serious problem as regards the first process is the accumulation of oxygen that is left behind the escaping hydrogen flow (Sasaki, 2008). According to recent numerical calculations of multi-component hydrodynamic flows (Sasaki, 2008), the escape flux of hydrogen is higher than that of oxygen. Thus, EUV-generated oxygen is inevitably accumulated in the atmosphere, eventually leading to a shutdown of the hydrodynamic escape itself (Sasaki, 2008). The escape amount of oxygen by means of the second process depends strongly on the activity of the ancient Sun, which is highly uncertain (e.g., Kulikov et al., 2007). In addition, more accurate evaluation of interactions between charged particles in the solar wind and planetary atmospheres, using a three-dimensional multi-species magnetohydrodynamic (MHD) model, indicates that the escape rate of oxygen is much lower than previously thought (Terada et al., 2009).

A serious problem associated with the third process is the lack of a driving force for surface replacement (e.g., Gillmann et al., 2009). The upper limit of oxygen removal caused by surface oxidation is estimated to be 0.1 times than an amount of surface water equivalent to that of the terrestrial oceans (hereafter referred to as TO; 1.4×10^{21} kg), based on the high average rate of volcanism over Venus' history (e.g., Gillmann et al., 2009). Recently, Hamano et al. (2013) proposed a new idea, namely that atmospheric oxygen could be removed through oxidation of a giant-impact-induced magma ocean. They showed that terrestrial planets are divided into two types, Earth-like ocean-covered planets (Type-I) and Venus-like dry planets (Type-II), a difference which appears to be correlated with distance from the planet's host star. If Venus belongs to the latter, "Type-II" planets, such a magma ocean (if affected by active thermal convection) may behave as a massive sink for atmospheric oxygen. However, the semi-major axis of the current orbit of Venus, 0.72 au, is very close to that which defines the boundary between the two types of planet, 0.6–0.8 au. Thus, it is not clear whether or not Venus belongs to the Type II planetary category (Hamano et al., 2013).

Here I propose a new mechanism, called "impact-driven planetary desiccation", to explain the water loss from steam-covered proto-Venus. A clue to the fate of surface water on Venus lies in those many impact craters on the Moon and Mars. Venus should have suffered similar impact bombardment at the same time as those on the Moon and Mars. I focus on such intense impact bombardment during the terminal stage of planetary accretion (e.g., Bottke et al., 2010) as the generator of reducing agents on planetary surfaces. Hypervelocity impacts onto proto-Venus during the terminal stage of planetary accretion are expected to have released a significant amount of fine-grained, highly reactive rocky materials into the atmosphere. At the same period, the accumulation of oxygen would proceed on proto-Venus via the photodissociation of the steam atmosphere and subsequent hydrogen escape into space as discussed above. The ejected rocks due to hypervelocity impacts are expected to remove the accumulated oxygen via the oxidation of iron-bearing rocks, i.e., $2FeO(s) + 1/2O_2(g) \rightarrow Fe_2O_3(s)$. As a result, hypervelocity impacts cause net desiccation of the atmosphere via oxidation of the planetary crust/mantle.

The objective of this study is to assess the significance of impact-driven planetary desiccation on steam-covered proto-Venus quantitatively based on impact physics and the impactor population at the terminal stage of planetary accretion. I calculated the cumulative mass of rocky ejecta on proto-Venus based on a number of previous studies on impact-driven excavation. Then, the possible amount of removed water is discussed.

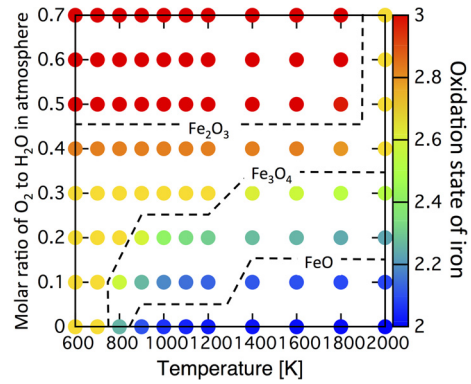

Fig. 1. Oxidation state of iron as a function of the molar ratio of O_2 to H_2O in a steam atmosphere and of temperature. The oxidation states of FeO, Fe_3O_4, and Fe_2O_3 correspond to 2, 8/3, and 3, respectively. The elemental ratio of H to Fe was fixed at H:Fe = 2:1. The total pressure was set to 300 atm. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

2. Numerical model

I constructed a numerical model using a Monte Carlo approach to include the effects of the stochastic nature of impact bombardment from the size, velocity and angle distributions of impactors during the terminal stage of planetary accretion. The excavated mass and depth after each impact event were calculated analytically. Then, the cumulative mass of non-oxidized ejecta through the intense impact bombardment was calculated. In this section, I describe the details of the model. The capability of rocky ejecta for oxygen removal is discussed in Section 2.1. The procedure to calculate the excavated mass at each impact event and the size of ejected particles are presented in Section 2.2. The reaction cross-section of rocky ejecta is an important factor to discuss the oxygen removal efficiency of rocky ejecta. The size and velocity distribution of impactors at the terminal stage of planetary accretion is described in Section 2.3. I discuss how to calculate the possible amount of removed oxygen at the end of the impact bombardment in Section 2.4. The effect of nonrenewable oxidized deposits is included in the calculation.

2.1. The oxygen removal efficiency

The water-removal efficiency (α) of impact-generated ejecta, including the effect of hydrogen escape, was calculated stoichiometrically at 10.6 g kg^{-1} based on the average FeO content on the Venusian surface (Surkov et al., 1984, 1986), 8.6 wt%. To remove an amount of surface water equivalent to that of the terrestrial oceans (TO; 1.4×10^{21} kg), an impact-generated ejecta mass of 1.3×10^{23} kg, corresponding to a basaltic crust/mantle of 90 km, is required.

For the calculations, it is assumed that ferrous iron is oxidized to ferric iron via the following oxidation reactions,

$$6FeO(s) + O_2(g) \rightarrow 2Fe_3O_4(s) \quad (1)$$

$$4Fe_3O_4(s) + O_2(g) \rightarrow 6Fe_2O_3(s) \quad (2)$$

The net reaction is described by $4FeO(s) + O_2(g) \rightarrow 2Fe_2O_3(s)$. Thus, it is necessary to address whether the above reaction proceeds in the forward direction. The chemical composition of the Fe–H–O system in thermal and chemical equilibrium was investigated using the Lewis code (Gordon and McBride, 1994). Fig. 1 shows the oxidation state of iron in the presence of excess oxygen as a function of the molar mixing ratio of oxygen to water

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