



The molecular composition of impact-generated atmospheres on terrestrial planets during the post-accretion stage



Hideharu Kuwahara ^{a,*}, Seiji Sugita ^{a,b}

^a Department of Complexity Science and Engineering, The University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8561, Japan

^b Department of Earth and Planetary Science, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

ARTICLE INFO

Article history:

Received 12 July 2014

Revised 4 May 2015

Accepted 8 May 2015

Available online 21 May 2015

Keywords:

Impact processes

Atmospheres, composition

Terrestrial planets

ABSTRACT

Both geochemical measurements and theoretical calculations suggest that impact degassing from meteoritic materials after the completion of main phase of planetary accretion may have produced a large fraction of the early terrestrial atmospheres. However, the molecular compositions of such impact-generated atmospheres are not well constrained because the thermodynamic cooling path, which controls the chemical reactions in impact-induced vapor, has not been investigated extensively. In this study, we theoretically assess the chemical reactions within impact-induced vapor that cools adiabatically until the pressure equilibrates with the ambient atmosphere.

The calculation results indicate that there are two primary controlling factors for the cooling path: impact entropy gain and atmospheric pressure. The former is mainly determined by both impact velocity and the presence/absence of an ocean. The degree of atmospheric effect depends on vapor plume size. For large impacts, atmospheric containment of vapor expansion is inefficient. However, the expansion of small vapor plumes is contained by the pre-existing atmosphere and their terminal molecular composition is controlled by this process. This is because whether a chemical reaction quenches during adiabatic cooling or during subsequent radiative cooling would depend on the cooling transition temperature, at which adiabatic expansion stops and radiative cooling takes over. For high atmospheric pressures and/or the vapor generated by high-velocity impacts, adiabatic expansion will cease at higher temperatures than typical quenching temperatures. Thus, the molecular composition of the vapor will not greatly depend on the impact velocity. The calculation results suggest that the molecular composition of the impact-induced vapor would vary widely (i.e., CH₄/CO ratios) even if the compositions of the impactors are the same. More specifically, the impact-induced vapor generated by lower velocity impacts may be rich in CH₄. Given average impact conditions on terrestrial planets, these calculation results further suggest that impact-generated atmospheres may have been rich in CH₄ on Mars and an ocean-covered Earth and rich in H₂ and CO on land-covered Venus and super Earths.

© 2015 Elsevier Inc. All rights reserved.

1. Introduction

The molecular composition of early terrestrial atmospheres is extremely important for understanding climatic conditions and prebiotic chemistry, especially at the time life was born on Earth and perhaps on Mars. For example, a CH₄-rich atmosphere on early terrestrial planets has been invoked as a solution for the faint young Sun problem (Sagan and Mullen, 1972; Kiehl and Dickinson, 1987; Pavlov et al., 2000; Haqq-Misra et al., 2008). Thus, the possibility of the abiotic formation of CH₄-containing atmospheres on early terrestrial planets has been investigated

rather extensively (Kress and McKay, 2004; Kasting, 2005; Hashimoto et al., 2007; Schaefer and Fegley, 2010). However, the presence of such an atmosphere during the prebiotic stage is still highly controversial.

The estimation of the molecular composition of early terrestrial planetary atmospheres requires knowledge on both the source of volatiles and outgassing processes. The bulk elemental abundance of the volatile sources largely determines the overall redox states of early terrestrial atmospheres. Thus, the elemental abundance of a planetary atmosphere varies greatly depending on its volatile sources. Previous studies have discussed mainly the oxidation state of early atmospheres based on that of possible volatile sources (e.g., Hashimoto et al., 2007; Schaefer and Fegley, 2010; Hirschmann, 2012).

* Corresponding author.

E-mail address: kuwahara@astrobio.k.u-tokyo.ac.jp (H. Kuwahara).

In contrast, the influence of the thermodynamic paths of outgassing processes on the molecular composition of the degassing vapor has not been investigated extensively. However, cooling paths of the vapor should affect the thermodynamic stability of the molecular composition, especially in impact degassing. In fact, the above studies based on chemical equilibrium calculations indicate that the molecular composition of the vapor with a given elemental abundance could vary greatly depending on temperature and/or pressure (Hashimoto et al., 2007; Schaefer and Fegley, 2010). For instance, the CH₄/CO ratio of chondritic vapor may vary greatly as a function of pressure and temperature. Because pressure and temperature in expanding impact-degassed plume would change with time, its molecular composition would vary as a function of time. Furthermore, its terminal molecular composition also change depending on their cooling rate. In order to address these issues, one must consider the dynamic aspect of impact degassing process, such as adiabatic expansion and radiative cooling. However, such dynamic aspects of chondritic vapor has not been investigated extensively. These species have different chemical properties, and thus, the climates and nonequilibrium-reaction processes would also be different, strongly depending on molecular compositions, even if the bulk oxidation states of the atmosphere are the same (e.g., Zahnle, 1986; McKay and Borucki, 1997).

Based on theoretical predictions, the source of volatiles for terrestrial planets could have varied with time evolution. During the main accretion phase, terrestrial planetary atmospheres are thought to have been generated by the capture of the solar nebula (e.g., Hayashi et al., 1979) and volatiles degassed from the magma ocean (e.g., Abe and Matsui, 1985). Such hybrid atmospheres from solar nebula/accreting materials would have been very reducing, rich in H₂ and CO (Hashimoto et al., 2007). However, both theoretical and geochemical studies indicate that such very reducing primordial atmospheres may have been efficiently lost by a giant impact during the terminal phase of planetary accretion (Genda and Abe, 2005; Stewart and Mukhopadhyay, 2013; Tucker and Mukhopadhyay, 2014). If this is the case, degassing by subsequent volcanic activity is thought to be the dominant source for the terrestrial atmosphere. However, the isotopic composition of volatiles in the terrestrial mantle cannot explain the characteristics of the present Earth's atmosphere as we discuss in the following section. Therefore, other sources would be required as a part of the present atmosphere, such as the late accretion of volatiles with meteoritic impact after magma ocean solidification (e.g., Chyba, 1990; Albarède, 2009).

In this study, we focus on impact degassing of volatiles from chondritic materials based on a consideration of the cooling path of impact-generated vapor plumes, and we discuss the implications of the results for the molecular composition of early atmospheres on terrestrial planets during the post-accretion phase. In Section 2, we discuss the importance of the late-impact delivery of volatiles for terrestrial planetary atmospheres, in Sections 3 and 4 we describe our models, in Section 5 we show the calculation results, in Section 6 we discuss the implications of our results for the earliest atmosphere of terrestrial planets, and in Section 7 we summarize our study.

2. Impact delivery of volatiles after magma ocean solidification

An efficient atmospheric loss during the giant impact stage and geochemical constraints on isotopic composition of noble gases supports that the impact degassing from late-accreting materials after magma ocean solidification have greatly contributed to the formation of the early terrestrial atmosphere than previously thought, as we discuss in the following.

In comparison with the solar abundance, noble gases in the volatile inventory of terrestrial planets are much more depleted than H, C, and N (e.g., Halliday, 2013). If all terrestrial volatiles were of solar nebula origin, the currently observed noble gas abundance in the present terrestrial atmosphere would require selective loss in noble gases to the space. This is because incorporation of noble gases into core is highly unlikely. However, such a simple view is not possible as the origin of the present terrestrial atmosphere as discussed in previous studies (e.g., Zahnle et al., 2010 and references therein). For example, Ne and N, which have similar atomic mass, are equally abundant in the solar composition. Thus, the Ne/N ratio of the terrestrial atmosphere would be close to unity if the origin of terrestrial volatiles is mainly the solar nebula because the mass fractionation by atmospheric escape between Ne and N would be limited. However, Ne is depleted relative to N on terrestrial planets by more than several orders of magnitude. Consequently, it is now widely believed that the solar nebula captured by the gravity of a protoplanet cannot be the only source for the terrestrial atmosphere and that other sources, such as degassing from meteoritic materials, must have made a major contribution (e.g., Brown, 1949). In fact, the abundance pattern of volatiles on terrestrial planets are approximately chondritic (e.g., Marty, 2012; Halliday, 2013).

If major atmospheric erosion occurred during the accretion phase, the degassing of volatiles after the formation of planets would have largely controlled the composition of post-accretion terrestrial atmospheres. A recent theoretical study shows that giant impacts during the late accretion phase may have efficiently blown off pre-existing atmospheres if protoplanets were covered with oceans (Genda and Abe, 2005). Calculations on the thermal evolution of magma oceans overlaid with a steam atmosphere show that the timescales of water condensation for Mars (i.e., 0.1 Myr) and Earth (i.e., 1.5 Myr) may have been shorter than a typical interval between giant impacts (i.e., 5 Myr), whereas the timescale of water condensation for Venus (i.e., 10 Myr) may not have been shorter than the average interval (Lebrun et al., 2013). Consequently, most of the pre-existing atmospheres may have been lost during the stage of giant impacts for at least Mars and Earth. Nevertheless, it is also noted that most of primordial oceans are estimated to survive atmosphere-stripping giant impacts (Genda and Abe, 2005). Such selective loss of an atmosphere compared to an ocean is actually consistent with the geological observations that the H/N and H₂O/Xe ratios of terrestrial planets are higher than any types of primitive materials (Halliday, 2013; Tucker and Mukhopadhyay, 2014; Dauphas and Morbidelli, 2014). If the efficiency of atmospheric loss during the main-accretion phase was very high, the contribution of late-impact delivery of volatiles to the terrestrial atmosphere is most likely significant.

The high abundances of highly siderophile elements (HSEs) in silicate mantles of many terrestrial planets (i.e., Vesta, the Moon, Mars, Earth) suggest that late accretion of chondritic materials, the so-called late veneer, on terrestrial planets after core formation may have been a common phenomenon in the inner Solar System (Dale et al., 2012; Day et al., 2012). Thus, terrestrial planetary atmospheres during the post-accretion stage would have been mainly generated by outgassing from magmas and late-impact delivery of volatiles. Furthermore, the isotopic composition of nitrogen on the Earth surface is similar to carbonaceous chondrites, but that of mantles are lighter and more solar-like (e.g., Marty, 2012; Cartigny and Marty, 2013). Such isotopic compositions of terrestrial nitrogen may reflect the overprint of the late veneer. Although these isotopic heterogeneity can also be achieved by the mass fractionation of gas molecules in primordial atmospheres,

Download English Version:

<https://daneshyari.com/en/article/8136124>

Download Persian Version:

<https://daneshyari.com/article/8136124>

[Daneshyari.com](https://daneshyari.com)