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Protoatmospheres and Surface Environment of Protoplanets

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Abstract Protoatmospheres and surface environment of terrestrial protoplanets during the oligarchic accretion phase and the giant impacts phase are discussed from theoretical points of view. Mars-sized protoplanets form during the stage of the oligarchic growth. Since protoplanets are formed from more or less ‘local’ planetesimals, the surface environment of the accreting protoplanets depends on availability of volatile material in planetesimals. Even if no volatile-bearing planetesimals are available, a gravitationary captured solar composition atmosphere is formed during accretion. In such cases the surface temperature is always kept under the melting temperature of mantle silicate and only a subsurface magma ocean is formed. Core formation proceeds under dry conditions, and volatile elements are not partitioned into metallic iron. Accretion of water-bearing planetesimals results in impact degassing. A surface hydrous magma ocean forms in response to the thermal blanketing effect of the proto-atmosphere. Then, some volatile materials dissolve into the magma ocean. If we consider reaction with metallic iron, the proto-atmosphere is likely to be rich in hydrogen. In addition, a large amount of hydrogen may be partitioned into metallic iron under high pressure, and delivered to the core. In the stage of giant impacts, both dry and water-bearing protoplanets collide on the proto-Earth. Substantial amount of proto-atmosphere (including water vapor) survives giant impacts. Moreover, giant impacts on protoplanets with oceans result in relative concentration of water against other gases.

Keywords Protoplanet · Protoatmospher · Giant impact · Planetary accretion · Water

1 Introduction

Recent planetary formation theory suggests two stages of planetary formation; the stage of oligarchic growth (e.g., Kokubo and Ida 1998) followed by the stage of giant impacts (e.g., Chambers and Wetherill 1998). In the oligarchic accretion phase, Mars-sized protoplanets

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are formed within about one million years through frequent small impacts. In the giant impacts phase, Earth-sized planets form through collisions among mars-sized protoplanets in about 100 million years. Based on such view of planetary accretion, we discussed the protoatmosphers and surface environment of protoplanets during their formation.

2 Wetness of Planetesimals

H_2O is a quite abundant material. The solar composition gas contains H_2O as much as 2–3 times of rocky materials. Thus, availability of H_2O in condensed phase is basically controlled by the disk temperature. To estimate the temperature distribution in the passive disk, Hayashi's model (Hayashi 1981) is widely accepted. This model suggests condensation of H_2O occurs at 2.7 AU from the Sun. At 1 AU, the Earth orbit, the disk is too warm to form hydrous minerals. Thus, according to this model, planetesimals are dry at the Earth orbit. However, recent theory suggests cool nebla, so that large amount of water can be trapped in planetesimals at the Earth orbit. Hayashi's model assumes a transparent disk in which dust particles are directly heated by the solar radiation. However, the disk contains so much fine dust that materials near the mid plane are shadowed by near surface particles. Such view is supported by observations of circumsteller disks (Chiang and Goldreich 1997; Chiang et al. 2001). This results in much cooler mid plane temperature. Such disk model suggests condensation of H_2O occurs even at 0.7 AU, around Venusian orbit, unless the mid plane is significantly heated by other mechanisms. Heating by short-lived isotopes is not enough to keep the disk materials from freezing. Gravitational energy released by the disk accretion to the Sun seems the only possible heat source that can make dry mid plane. Thus, unless the planetesimals were formed in an accreting disk, planetesimals can contain significant amount of ice even at the Earth-orbit (Machida and Abe 2006, 2007, 2010).

As the result of planetesimal formation, fine dust decreases. Then, the disk becomes transparent and ice starts sublimation. Thus, the water content in the planetesimals accreting to the protoplanet is controlled by the competition between sublimation and accretion. This process is very complicated and our initial estimate (Machida and Abe 2006, 2007, 2010) suggests highly variable water content depending on initial condition and sublimation efficiency. It is interesting to note that the expected water content is likely size dependent; larger bodies, which grow up faster, retain water, but smaller bodies, which grow up slower, get dry. This may imply protoplanets are somewhat wetter than meteorites. Thus, planetesimals in the zone between 0.7 and 2.7 AU can be either wet or dry depending on the disk condition.

3 Protoplanets in the Oligarchic Accretion Phase

During the early phase of planetary accretion, protoplanets collect more or less 'local' planetesimals. As we discussed in the previous section, planetesimals can be either wet or dry in the terrestrial planet region. Hence, we consider both cases of protoplanet formation from dry planetesimals and wet planetesimals.

3.1 Formation of Protoplanets from Dry Planetesimals

It must be noted that the solar nebula gas exists during the oligarchic accretion phase. Thus, even if no volatile-bearing planetesimals are available during accretion, protoplanets would have attracted surrounding gas to form a distended solar-composition (H_2–He) atmosphere, as shown by Hayashi et al. (1979, 1985) and Nakazawa et al. (1985).

Since this atmosphere is extended and made of light gas, mainly by hydrogen, pressure is very low. Though the blanketing effect is not so strong while the protoplanet is smaller than about Mars-size, it can keep the surface around 1000 kelvin. The surface temperature is kept under the melting temperature of mantle silicate and only a subsurface magma ocean is formed by impact heating. Hence, core formation proceeds under dry conditions, and volatile elements are not partitioned into metallic iron, though some amount of water should be formed through reaction of the atmosphere with rock.

3.2 Formation of Protoplanets from Wet Planetesimals

Accretion of water-bearing planetesimals results in many phenomena. Impact degassing starts when the protoplanet reaches about the Moon size. A degassed atmosphere is sometimes called a ‘steam atmosphere’, because the major volatile contained in planetesimals would be water. However, if we consider reaction with metallic iron, it is likely to be rich in hydrogen. In addition the solar nebula gas exists during this phase. Thus, the degassed water vapor is injected at the bottom of the thin solar composition atmosphere. Then, the thermal structure of the lower atmosphere should be similar to that of the classical steam atmosphere.

Water vapor shows strong blanketing effect (e.g. Abe and Matsui 1985, 1986, 1988; Matsui and Abe 1986a, b; Zahnle et al. 1988). However, since the actual energy release occurs at each planetesimal impact, heating is intrinsically local and intermittent. The atmosphere may cool before the next planetesimal impact if the mean impact interval of planetesimals is longer than the cooling time of a hot atmosphere (Abe 1988; Rintoul and Stevenson 1988).

Nishikawa (personal communication) simulated the evolution of steam atmospheres with directly treating each planetesimal impact. Figure 1 shows a typical result. Here, we consider local heating by impact and ejecta reentry and radiative cooling in a steam atmosphere. Atmospheric pressure varies with impact degassing and condensation of water. The cooling time is the longer for the thicker atmosphere. Size distribution of planetesimals is assumed to follow power law with cumulative exponent 2.5 (Kokubo 1996). Average water content of planetesimals is 1% in this calculation. Though the surface temperature stochastically changes by each impact, the surface temperature is kept above the melting temperature of silicate.

It is interesting to note that small frequent impacts sustain high surface temperature once a thick atmosphere is formed by an impact of large planetesimal ($\sim 10^{20}$ kg). Thus, a surface magma ocean is sustained during this stage. Volatile materials dissolve into the magma ocean and react with metallic iron (Abe et al. 2000).

4 Protoplanets in the Giant Impacts Phase

During this phase we can expect giant impacts among protoplanets formed at various distance from the Sun. It means collision among protoplanets with various volatile content. As discussed in the previous sections, a protoplanet has either a solar-composition or a mixed atmosphere.

Giant impacts affect the atmosphere in several ways. One possible effect is blow off of the atmosphere by shock wave induced by the impact. The loss fraction of the atmosphere

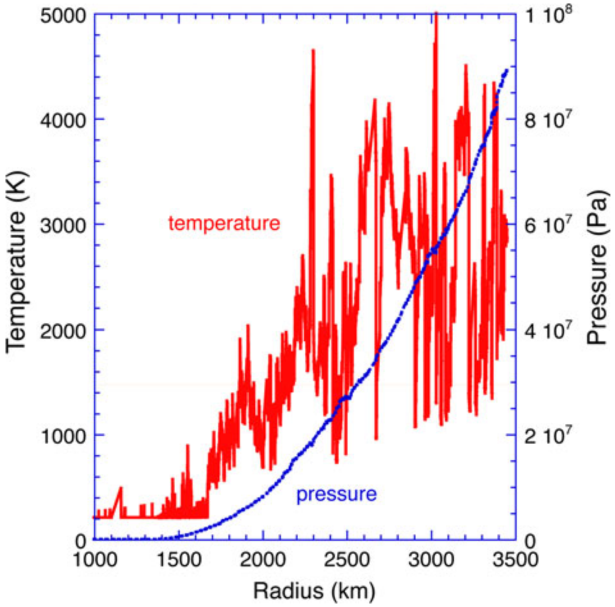

Fig. 1 Simulated surface temperature and pressure of protoplanet during accretion. Though the surface temperature stochastically changes by each impact, the surface temperature is kept above the melting temperature of silicate

is quite sensitive to the surface condition of the protoplanet (Genda and Abe 2003, 2005). When the surface is not covered by an ocean, the loss fraction is almost proportional to the ground motion velocity. It is insensitive to the atmospheric properties. The significant loss occurs only when the ground motion is close to the escape velocity (Genda and Abe 2003). One third of original atmospheres are expected to survive the sequence of such impacts (Genda and Abe 2005). On protoplanets with oceans, the atmosphere is efficiently blown away by the impact, while water ocean survives (Genda and Abe 2005). Hence, giant impacts on such planets result in relative enrichment of water against other gases.

Another loss mechanism is the thermal escape of the atmosphere heated by an impact. Giant impacts heat up the protoplanet up to 10 thousand kelvins. It is obviously high enough to induce hydrodynamic outflow of hydrogen, which starts at about 4000 K on an Earth-sized planet. However, at such condition, silicate is evaporating and the atmosphere is mixed with oxide and metal (Genda and Abe 2004). Since the mixing of heavy material raises the mean molecular weight, the outflow is suppressed. The characteristic time for the hydrodynamic loss is much longer than the cooling time, we think that the loss would not occur.

Thus, a substantial amount of the proto-atmosphere (including water vapor) survives giant impacts. Moreover, giant impacts on protoplanets with oceans result in relative concentration of water compared to other gases. Whether or not the protoplanet has water ocean depends on the distance from the central star. The time scale of protoplanets migration is longer than that of condensation or evaporation of oceans. Hence, the place of collision is rather important than the original position of water-bearing protoplanets. When collision of water bearing protoplanets occurred somewhere between the Venusian and Martian orbits (Abe 1993), the protoplanets should have oceans and water would be enriched. Thus, planets formed near Earth orbit are likely enriched in water than those near Venus orbit or those experienced no giant impacts (Mars?)

It is well known that a pure solar composition atmosphere could not be the direct ancestor of the present atmosphere of a terrestrial planet (Brown 1949; Suess 1949), because it contains large amount of rare gases compared to other gases. However, since it is mixed with degassed components through the giant impacts with wet protoplanets, most of gases other than rare gases are derived from degassed components. Thus, such a mixed protoatmosphere can be the direct ancestor the present atmosphere.

Impacts obviously produces a deep magma ocean and partially vaporise the mantle. The magma ocean cools relatively rapidly (Abe 1997) but we can expect redistribution of volatile materials between the atmosphere and mantle. Volatile materials dissolved in the molten mantle is likely degassed upon the solidification of the magma ocean. However, volatile materials dissolved in the metalic iron would be kept in the core, and affects both the core and the atmosphere compositions. It seems quite difficult to achieve equilibrium (Sasaki and Abe 2007) during this process. Thus, the difference of the core composition between the dry and water-bearing protoplanets may be partly preserved. However, this process is not well understood yet.

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