FORMATION AND EARLY EVOLUTION OF ATMOSPHERE AND OCEAN ON THE EARTH.

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Introduction: The Earth is the only planet to harbor life, as we know so far. Adequate amount of water and atmosphere on the Earth has been thought to be essential for the emerge and evolution of life [1]. Therefore, investigating the origin and formation of ocean and atmosphere on the Earth is important, and it would answer the questions why we are here and whether or not another life exists in the universe.

We have a piece of geological and geochemical evidence that constrains the age of the ocean and atmosphere on the Earth. The existence of sediments implies that ocean already exist on the Earth at least 3.8 Gyr ago [2]. Moreover, the oxygen isotopes in very old zircon imply that a substantial amount of liquid water existed around 4.3 Gry ago [3]. According to isotopic compositions of the noble gases in the atmosphere and mantle, most of the atmospheric volatiles must have degassed to the surface by 4.0 Gyr ago [4]. Since the Earth was formed 4.5 Gry ago, volatile elements forming the ocean and atmosphere should be supplied during or just after the Earth's formation.

In this workshop, we would like to review mechanisms of supply and loss of volatiles on the terrestrial planets. We will discuss the effects of giant impacts on the formation of the ocean and atmosphere.

Supply and Loss of Volatiles on the Earth: Planets form in a protoplanetary disk composed of dust and gas. Terrestrial planets are made mainly from dust. It has been generally thought that the Earth's building blocks around 1 AU have no volatiles that compose the ocean and atmosphere. On the other hand, the objects beyond the asteroid belts (~ 2 AU) contain a significant fraction of volatiles [5]. Therefore, some mechanisms to supply or produce volatiles on the Earth are required for the Earth to possess the ocean and atmosphere. Supply process of volatile-rich objects from outside the terrestrial planet region is highly related to the planet formation theory. Recent planet formation theory suggests that the behavior of forming Jupiter have a great influence on this supply process [6]. For example, great migration of Jupiter called "The Grand Tack Model" would provide sufficient amount of water on the Earth [7].

Loss of volatile elements from planets has an influence on the volatile budget on the terrestrial planets. Several volatile loss mechanisms have been proposed so far, such as hydrodynamic escape [8], loss by giant impact [9, 10], and so on. Loss of water from Venus is important to the habitability of planets.

Cooling of Magma Ocean and Formation of Ocean: It is generally accepted that many giant impacts occur during the last stage of terrestrial planet formation. The energy released by a giant impact is huge, and it can raise the temperature of the whole proto-Earth by about 5000K in average. Therefore, the planet should be wholly molten just after a giant impact. Cooling process from molten Earth is important to formation of the ocean and atmosphere.

We have investigated the cooling process using coupled model of magma ocean, atmosphere, and space [11]. The Earth solidifies within several million years, and most of water is degassed but no escape occurs. In contrast, the magma ocean on the planet around Venus' orbit can be sustained until almost all water is lost to the space. In this case, the typical duration of magma ocean is about 100 million years. Planet formation theory suggests that water can be supplied on Venus as well as Earth. Therefore, drastic loss of water only on Venus is consistent with the present dry Venus.

Steam atmosphere fomed just after the solidification of magma ocean rapidly cools, and the ocean forms in 1000 years through the intense rainfall [12]. The rain drops is very hot (~ 300 ^{o}C) and the rain fall rate is very high (~ 500 cm/yr), which is ten times as high as that in tropical region on the present Earth.

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