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Primordial atmosphere incorporation in planetary embryos and the origin of Neon in terrestrial planets

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ABSTRACT

The presence of Neon in terrestrial planet mantles may be attributed to the implantation of solar wind in planetary precursors or to the dissolution of primordial solar gases captured from the accretionary disk into an early magma ocean. This is suggested by the Neon isotopic ratio similar to those of the Sun observed in the Earth mantle. Here, we evaluate the second hypothesis. We use general considerations of planetary accretion and atmospheric science. Using current models of terrestrial planet formation, we study the evolution of standard planetary embryos with masses in a range of 0.1–0.2 M_{Earth}, where M_{Earth} is the Earth's mass, in an annular region at distances between 0.5 and 1.5 Astronomical Units from the star. We determine the characteristics of atmospheres that can be captured by such embryos for a wide range of parameters and calculate the maximum amount of Neon that can be dissolved in the planet. Our calculations may be directly transposed to any other planet. However, we only know of the amount of Neon in the Earth's solid mantle. Thus we use Earth to discuss our results. We find that the amount of dissolved Neon is too small to account for the present-day Neon contents of the Earth's mantle, if the nebular gas disk completely disappears before the largest planetary embryos grow to be ~0.2 M_{Earth}. This leaves solar irradiation as the most likely source of Neon in terrestrial planets for the most standard case of planetary formation models.

1. Introduction

The atmospheres of Mars, Venus and Earth have evolved through time and bear the signature of late processes such as the post-accretion addition of a volatile-rich veneer and/or mantle degassing. ^{3}He emissions at mid ocean ridges demonstrate that the Earth's mantle is still losing primordial gases today, e.g. Clarke et al. (1969) and Craig et al. (1975), indicating long-term storage in the deep mantle. Gaseous species that are found in the Earth's mantle have probably been inherited from solar gases captured during planetary formation (e.g. Sasaki, 1999). This is particularly true for Neon, the second noble gas and the fifth element in the solar system by order of abundance, because its 20Ne/22Ne isotopic ratio is "solar-like" (Sarda et al., 1988; Honda et al., 1991). Relative to the isotopic composition of the atmosphere, the 20Ne/22Ne ratio in the source of oceanic basalts takes values that are larger than 12.5 and that can be as high as 12.8, close to the solar value of ~13.8 (Mukhopadhyay, 2012; Yokochi and Marty, 2004; Kurz et al., 2009; Colin et al., 2015; Moreira and Charnoz, 2016). Two processes have been invoked for account for the presence of solar-like Neon in the Earth's mantle. Solar gases were present in the atmospheres of planetary embryos and got dissolved in an early magma ocean (Sasaki, 1999). Alternatively, solar gases may have been carried by solar wind and got implanted in planetary precursors (Trieloff, 2000; Raquin and Moreira, 2009; Moreira and Charnoz, 2016).

According to our current understanding of terrestrial planetary formation, the Earth likely grew from a swarm of planetary embryos shortly after the formation of the oldest known solids within of the solar system, Calcium Aluminium Rich inclusions (CAIs) found in meteorites with an age of 4.567 Gy (Amelin et al., 2002). According to 182Hf-182W studies of mantle-derived samples, the Earth's core was last equilibrated within the first 50 Myrs (Kleine et al., 2009). The planetary embryos that coalesced into Earth, however, were formed much earlier, only 1–2 millions years after the CAIs. There are two competing theories of embryo formation.

The standard model of planetary embryo formation involves a swarm of planetesimals (~10 km objects at 1 AU from the Sun) e.g. Greenberg et al. (1984). These planetesimals go through a phase of

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"runaway growth" with low velocity impacts that lasts less than 1 Myr. Numerical simulations show that the largest objects grow at much larger rates than their smaller neighbors, leading to the rapid formation of a locally dominant body. Due to rapid material depletion in its surroundings and to the progressive dynamical excitation of neighboring planetesimals, however, accretion stops when the largest local body reaches the so-called "Isolation Mass" (Lissauer, 1987). Such bodies have masses between those of Moon and Mars, depending on the local disk surface density and distance to the Sun. In the absence of external perturbations, locally dominant bodies are separated from their neighbors by about 10 mutual Hill radii, as in the "Grand Tack" model, see Walsh et al. (2011). In such conditions, they are dynamically isolated and it takes another ~100 Myrs for them to collide with one another and form Earth-sized planets. Thus, even though Earth may have accreted in 100 Myrs, its embryos may have already existed one million years or less after the formation of CAIs.

Recently, an alternative process of embryo formation has emerged, the so-called "Streaming Instability" model of Johansen and Klahr (2011). According to this model, embryos may have grown directly out of pebble-sized objects through an efficient accretion process enhanced by aerodynamic drag. In the Solar Nebula, dust coagulation leads rapidly to millimeter-sized objects at 1AU distance (Brauer et al., 2008) and even larger objects if it occurs in a turbulent free region (Charnoz and Taillifet, 2011). These objects are marginally coupled to the ambient gas and settle rapidly to the mid-plane of the disk, expelling gas from the mid-plane. High-pressure regions collect pebbles with increasing efficacy through the so-called "streaming instability" process, leading to the growth of large bodies that eventually collapse gravitationally in a few orbits (Johansen et al., 2007). The maximum size of such bodies is not well constrained, but it seems possible that they reach sizes of at least of a few hundred kilometers or larger. In that case, "planetesimals" would not even exist and embryos may form directly in a very short time because of the coupled effects of accretion and aerodynamic drag. This process may account for the small mass of Mars (Levison et al., 2015) and may also explain the large initial dimensions of asteroids (Morbidelli et al., 2009).

Protoplanet formation takes a few millions years only and is accompanied by the gradual disappearance of the gas disk progressively due to photo-evaporation (Hillenbrand, 2005). A few million years later, the gas disk has completely evaporated (Gorti et al., 2009), leaving a population of planetary embryos that accrete to form planets.

According to the above sequence and timing of events, planetary embryos were kept immersed in a gaseous protoplanetary disk for a couple of million years, well before they could assemble into a fully grown planet. During this phase, while their mass was between 0.1 to 10% of that of Earth, they may have captured a primitive atmosphere composed of gas from the protosolar nebula with a solar composition. In this study, we determine the structure of such a proto-atmosphere. The mantle of the planetary embryos, if it was molten, equilibrated with the captured atmosphere, leading to the dissolution of noble gases in potentially significant quantities.

This problem has been addressed in the past literature, but the conclusions given were different. Sasaki and Nakazawa (1990) for example treated this issue for embryos with a range of mass from 0.5 to 1 M_{Earth} in a still present and massive disk. Using the geochemical constaints available at that time on Neon dissolution they concluded that the solar type atmosphere around the protoplanet should have started escaping before the planetary mass was lower than 0.6 M_{Earth}. In this paper we used updated models of planetary formation and updated geochemical constraints, which lead us to study embryos with mass of 0.1 and 0.2 M_{Earth} and compare the efficiency of the atmospheric dissolution process against estimations of the Neon concentration before the degasing of the mantle. Standard cases of recent models of planetary formation only produce Earth embryos as small as 0.1 to 0.2 Earth mass for the biggest objects when the gaseous disk is still massive and present (e.g. Walsh and Levison, 2016). We thus study a standard embryo of 0.1 to 0.2 M_{Earth} and use updated geochemical constraints which allows us to give different conclusions that the ones drawn in the previous literature.

2. Numerical method

2.1. Model

We assume that the atmosphere is spherically-symmetric and segues into the surrounding nebula at its outer radius r_{atm}, which will be defined below. For simplicity, we assume that the planet is much heavier than its atmosphere, which is appropriate for this study, implying that the atmosphere does not modify the gravity field due to the planet. The atmospheric structure is well described by the equation of hydrostatic equilibrium.

$$\frac{dP}{dr} = -\frac{GM_{core}\rho}{r^2} \tag{1}$$

where P and ρ are respectively the pressure and density of atmospheric gas, r the distance to the planet center, G the gravitational constant and M_{core} the planet mass.

The thermal structure can be obtained from the energy balance equation. The optical thickness is denoted by τ:

$$\tau \equiv \int_r^{r_{atm}} \kappa\rho\,\mathrm{d}r \tag{2}$$

If τ is smaller than 2/3 and provided that the radial temperature gradient is less than the adiabatic one, temperature obeys the following equation (Hayashi et al., 1979) :

$$T^4 = T_{disk}^4 + \frac{L}{8\pi\sigma r^2}\frac{1+3\tau/2}{2-3\tau/2} \tag{3}$$

In Eqs. (2) and (3), T and T_{disk} are the temperature of the atmosphere at radius r and the temperature in the disk, respectively, and κ is the Rosseland opacity.

If $\tau > 2/3$, the radial temperature distribution is given by the lesser of the adiabatic and radiative temperature gradients. Considering the ideal gas equation of state, the former is given by:

$$\frac{dT_{ad}}{dr} = -\frac{\gamma-1}{\gamma}\frac{GM_{core}\mu}{k_B r^2} \tag{4}$$

whereas the latter is given by:

$$\frac{dT_{rad}}{dr} = -\frac{3\kappa\rho L}{64\pi\sigma r^2 T^3} \tag{5}$$

where $\gamma = C_P/C_V$ is the adiabatic exponent and is equal to 7/5 in this study, k_B is the Boltzmann constant and μ the mass of a single molecule of gas taken to be 2.34 $\mathrm{m_{proton}}$. L is the energy flux passing through a sphere of radius r and is called luminosity. Rosseland opacities are taken from Baillié et al. (2015) (see below). If the radiative gradient is larger than the adiabatic one, the atmosphere is unstable to convection, implying that the radial temperature profile adjusts to that of a well-mixed convective layer, which is well described by the adiabatic gradient.

If the embryo surface is partially molten ($T > \approx 1500$ K), we may use Henry's law to calculate the concentration of dissolved Neon that is in equilibrium with the atmospheric value:

$$\mathrm{c} = \mathrm{s}\ \ P_i \tag{6}$$

where c is the concentration of the dissolved gas, s solubility and P_i the partial pressure of the gas. In the following, we integrate Eqs. (1) to (5) using a fourth order Runge–Kutta method for a wide parameter range.