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The origin of the neon isotopes in chondrites and on Earth

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ABSTRACT

We discuss the origin of the neon isotopic signatures in chondrites and in the terrestrial mantle. There are two primary possible origins for neon in the Earth's mantle. One origin is the dissolution of a dense primordial atmosphere with a solar composition of $^{20}Ne/^{22}Ne > 13.4$ into the mantle in a possible magma ocean stage during Earth's accretion. The second origin, developed in this study, is that mantle neon was already in Earth's parent bodies because of refractory grain irradiation by solar wind. We propose that solar wind implantation occurred early on dust within the accretion disk to allow such irradiation. Because solar wind implantation fractionates neon isotopes, the heavier isotopes are implanted deeper than the lighter ones because of different kinetic energies, and the process of implantation, if coupled with sputtering, leads to a steady state neon isotopic ratio ($^{20}Ne/^{22}Ne \sim 12.7$) that is similar to what is observed in mantle-derived rocks (12.5–12.9), lunar soil grains (~ 12.9) and certain gas-rich chondrites from all classes (enstatite, ordinary, rumuruti). Using a dust transport model in a turbulent and irradiated solar nebula, we estimated the equivalent irradiation age of a population of dust particles at three different distances from the sun (0.8, 1, 1.2 AU) and converted these ages into neon concentrations and isotopic ratios. The dust subsequently coagulated to form Earth's parent bodies, which have the mean neon isotopic composition of the irradiated dust (non-irradiated dust is assumed to be free of neon). If this scenario of solar wind implantation coupled with sputtering in the precursors of Earth's parent bodies is correct, it offers a simple alternative to the model of solar nebula gas incorporation by dissolution in a magma ocean.

1. Introduction

The origin of volatiles on terrestrial planets is a long-standing debate because it has major consequences in many subfields of the Earth and Planetary Science. Terrestrial planets are accreted with material that is depleted of moderately volatile elements, such as K, Rb or Pb (e.g., Albarède, 2009); therefore, these planets are expected to be depleted in highly volatile elements, such as C, H, N and the noble gases, and thus the question of these elements origins arises. Noble gases are the perfect tools to constrain possible origins of volatiles on terrestrial planets. These gases form a family of chemically inert elements, highly volatile and with a large mass spectrum from He to Xe. Chondrites and terrestrial planets, relative to the sun, are highly depleted in noble gases by several orders of magnitude compared to other elements, including other volatiles (e.g., C, N, and others). Noble gases have both radiogenic and "stable" isotopes, allowing them to be used to trace physical processes during planetary formation and evolution and to constrain these processes in time. Additionally, because they are strongly depleted in refractory material, noble gases are very sensitive to secondary processes involving solar gases, such as adsorption or solar wind implantation. Therefore, noble gases are ideal tools to trace physical processes involving dust/gas interactions in the accretion disk during solar system formation.

The neon isotopic signature allows us to constrain the process of noble gas incorporation into the parent bodies of terrestrial planets. Indeed, the "stable" $^{20}Ne/^{22}Ne$ ratio varies greatly in different solar system reservoirs (Fig. 1). Fig. 1 shows the isotopic compositions of solar wind, the estimated ratios of the Sun, different types of chondrites, the Earth's atmosphere, the mantle and the three main carriers of neon in chondrites (A, B and E). The cosmogenic end-member represents the production of three neon isotopes by spallation during the transfer of the meteorite from the asteroid belt to the Earth, which is a secondary process that is irrelevant to understanding the physical processes during the formation of the parent bodies of these objects. Neon A has been proposed to represent the composition of pre-solar grains, formed

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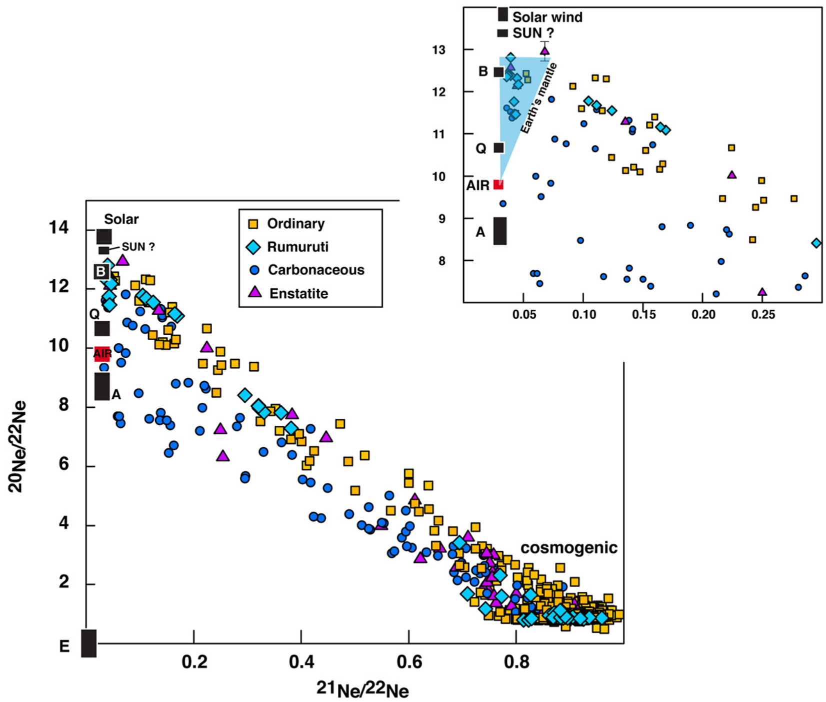

Fig. 1. Neon isotopes in terrestrial and extraterrestrial material. Four classes of chondrites are represented in this diagram. This figure is modified from Moreira (2013). Carbonaceous chondrites show a mixing of 3 components (Neon A Black, 1972a, 1972b, Neon B Black, 1972a, 1972b and Cosmogenic neon), whereas the other classes of chondrites show broadly a binary mixing between Neon B and Cosmogenic neon, although some Neon A could be present. Phase Q neon composition is also provided for comparison (Busemann et al., 2000), this may not be a major carrier of neon. The solar wind composition is derived from Grimberg et al. (2006). Because the solar wind can be fractionated compared to the sun, the recent estimate of Heber et al. (2012) for the sun's $^{20}Ne/^{22}Ne$ ratio is provided. The Earth's mantle domain is represented by the blue triangle in the inset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in red giant envelopes (e.g., Huss and Lewis, 1994). In pre-solar grains, there is a second end-member, neon E. Neon E composition is pure ^{22}Ne derived from the decay of ^{22}Na. This is, however, a trace component in chondrites (e.g., Huss and Lewis, 1994) and therefore will not be considered in this study as an important neon contributor. The solar wind neon isotopic composition has been recently precisely determined by Genesis probe targets that confirm previous estimates obtained on Apollo foils or lunar grains that were exposed to solar wind (Grimberg et al., 2006; Heber et al., 2009, 2012; Pepin et al., 2012). There is also the question of whether the solar wind composition reflects the solar composition because mass fractionation is induced during solar wind formation, and the recent estimate of the $^{20}Ne/^{22}Ne$ ratio of the sun was acquired using a model of fractionation in the solar wind (Heber et al., 2012). The $^{20}Ne/^{22}Ne$ ratio that was estimated for the sun is $13.4 \pm 0.2(2\sigma)$, lower than generally assumed (<13.8).

It has been suggested that mantle neon could be of solar origin by the dissolution of a primordial dense solar-like atmosphere into a magma ocean (Ballentine et al., 2005; Mukhopadhyay, 2012; Yokochi and Marty, 2004). Such a scenario may explain the neon isotopic signature in the mantle if the subduction of atmospheric neon occurs in the mantle; however, there are issues regarding the elemental pattern of the noble gases observed in the mantle that are incompatible with the dissolution of solar gases here (e.g., Moreira, 2013) and the Ar and Kr isotopic compositions (Holland et al., 2009; Raquin and Moreira, 2009), which are better explained by a chondritic origin of noble gases, rather than by the dissolution of solar noble gases into a magma ocean. In this study, we discuss the origin of neon on Earth as reflecting the neon "B" signature (e.g., Black, 1971, 1972a, 1972b), which is observed in gas-rich meteorites and on lunar soil. However, the neon B isotopic signature is estimated to be 12.5 (Black, 1971, 1972a, 1972b), lower than the highest $^{20}Ne/^{22}Ne$ measured on oceanic basalts ($\sim$12.9) (e.g. Mukhopadhyay, 2012; Yokochi and Marty, 2004), which therefore question the neon B as a possible primordial neon composition of the Earth.

Using a model of solar wind implantation coupled with sputtering, we show that the best $^{20}Ne/^{22}Ne$ ratio for the Neon-B component is $\sim$12.7, consistent with ratios measured from lunar soil grains, gas-rich meteorites and mantle-derived samples and is higher than a previous estimate based only on relatively few samples (Black, 1971, 1972a, 1972b). We also discuss the chronology of irradiation during the first stage of solar system formation using a dust transport model in the solar nebula. We propose that solar wind implanted neon into the dust in the inner solar system (0–1.2 AU) within a short period of time (a few Ky), before macroscopic grains and planetary embryos were formed.

2. The neon isotopes in the Earth's mantle

Since the study by Poreda and Radicati di Brozolo (1984), there have been many studies of neon isotopes in mantle-derived samples, producing a comprehensive data set that allows us to determine the neon isotopic composition of the mantle. Fig. 2 shows the neon isotope ratios of a large suite of Mid Ocean Ridge Basalt (MORB) samples, excluding two on-ridge hotspots called Shona and Discovery in the south Atlantic that have low $^4He/^3He$ (high $^3He/^4He$) (Moreira et al., 1995; Sarda et al., 2000), which instead can be considered OIB. Only samples with uncertainties lower than 5% are represented in this figure. The data dispersion reflects three different processes: the atmospheric contamination of mantle-derived magmas, the nucleogenic production of the ^{21}Ne, and mixing with a more primitive material (e.g., with lower $^{21}Ne/^{22}Ne$ ratio at a given $^{20}Ne/^{22}Ne$) (Kurz et al., 2005; Niedermann et al., 1997).

Atmospheric contamination decreases both isotopic ratios. Fig. 2a shows that most of the MORB samples have a $^{20}Ne/^{22}Ne$