



## Evolution of atmospheric xenon and other noble gases inferred from Archean to Paleoproterozoic rocks

G. Avice<sup>a,\*</sup>, B. Marty<sup>a</sup>, R. Burgess<sup>b</sup>, A. Hofmann<sup>c</sup>, P. Philippot<sup>d,e</sup>, K. Zahnle<sup>f</sup>,  
D. Zakharov<sup>g</sup>

<sup>a</sup> Centre de Recherches Pétrographiques et Géochimiques, CRPG-CNRS, Université de Lorraine, UMR 7358, 15 rue Notre Dame des Pauvres, BP 20, 54501 Vandoeuvre-lès-Nancy, France

<sup>b</sup> School of Earth and Environmental Sciences, University of Manchester, Oxford Road, Manchester M13 9PL, UK

<sup>c</sup> Department of Geology, University of Johannesburg, P.O. Box 524, Auckland Park 2006, South Africa

<sup>d</sup> Institut de Physique du Globe de Paris, Université Sorbonne Paris Cité, UMR 7154, Paris F-75238, France

<sup>e</sup> Géosciences Montpellier, Université de Montpellier, UMR 5243 CNRS, Place Eugène Bataillon, 34095 Montpellier, France

<sup>f</sup> NASA Ames Research Center, Moffett Field, CA 94035, USA

<sup>g</sup> Department of Earth Sciences, University of Oregon, Eugene, OR 97403, USA

Received 15 November 2017; accepted in revised form 16 April 2018; available online 26 April 2018

### Abstract

We have analyzed ancient atmospheric gases trapped in fluid inclusions contained in minerals of Archean (3.3 Ga) to Paleozoic (404 Ma) rocks in an attempt to document the evolution of the elemental composition and isotopic signature of the atmosphere with time. Doing so, we aimed at understanding how physical and chemical processes acted over geological time to shape the modern atmosphere.

Modern atmospheric xenon is enriched in heavy isotopes by 30–40‰  $u^{-1}$  relative to Solar or Chondritic xenon. Previous studies demonstrated that, 3.3 Ga ago, atmospheric xenon was isotopically fractionated (enriched in the light isotopes) relative to the modern atmosphere, by  $12.9 \pm 1.2$  (1 $\sigma$ )‰  $u^{-1}$ , whereas krypton was isotopically identical to modern atmospheric Kr. Details about the specific and progressive isotopic fractionation of Xe during the Archean, originally proposed by Pujol et al. (2011), are now well established by this work. Xe isotope fractionation has evolved from 21‰  $u^{-1}$  at 3.5 Ga to 12.9‰  $u^{-1}$  at 3.3 Ga. The current dataset provides some evidence for stabilization of the Xe fractionation between 3.3 and 2.7 Ga. However, further studies will be needed to confirm this observation. After 2.7 Ga, the composition kept evolving and reach the modern-like atmospheric Xe composition at around 2.1 Ga ago.

Xenon may be the second atmospheric element, after sulfur, to show a secular isotope evolution during the Archean that ended shortly after the Archean-Proterozoic transition. Fractionation of xenon indicates that xenon escaped from Earth, probably as an ion, and that Xe escape stopped when the atmosphere became oxygen-rich. We speculate that the Xe escape was enabled by a vigorous hydrogen escape on the early anoxic Earth. Organic hazes, scavenging isotopically heavy Xe, could also have played a role in the evolution of atmospheric Xe.

For 3.3 Ga-old samples, Ar-N<sub>2</sub> correlations are consistent with a partial pressure of nitrogen ( $pN_2$ ) in the Archean atmosphere similar to, or lower than, the modern one, thus requiring other processes than a high  $pN_2$  to keep the Earth's surface

\* Corresponding author at: California Institute of Technology, Department of Geological and Planetary Sciences, MC170-25, 1200 East California Boulevard, Pasadena, CA 91125, USA.

E-mail addresses: [gavice@caltech.edu](mailto:gavice@caltech.edu), [avice.guillaume@gmail.com](mailto:avice.guillaume@gmail.com) (G. Avice).

warm despite a fainter Sun. The nitrogen isotope composition of the atmosphere at 3.3 Ga was already modern-like, attesting to inefficient nitrogen escape to space since that time.

© 2018 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

**Keywords:** Noble gases; Xenon; Archean; Atmosphere; Escape

## 1. INTRODUCTION

The origin of the volatile elements in the Earth's atmosphere and mechanisms responsible for its subsequent evolution remain poorly understood (Marty, 2012). The elemental and isotopic composition of the Earth's atmosphere has been shaped by numerous events in the history of our planet including contributions from diverse extraterrestrial sources during the accretion, meteoritic and cometary impacts, mantle degassing, subduction with crustal recycling of volatile-rich lithologies and atmospheric escape. Despite the presence of a geological rock record, little is known about the state of the atmosphere during the Archean (4.0–2.5 Ga), an epoch covering one third of Earth's history and during which early forms of life emerged and evolved (Nisbet and Sleep, 2001). Some isotopic signatures in ancient sediments point to major differences in the composition of the atmosphere in the Archean and early Paleoproterozoic eons. For example, sulfur isotopes measured in rocks older than  $\approx 2.3$  Ga carry a mass-independent fractionation (MIF) signature originating from photochemical reactions involving UV photons in a  $O_2$ -poor atmosphere (Farquhar and Wing, 2003; Catling, 2014). Furthermore, an atmospheric composition very different from the modern one seems to be required to maintain a warm temperature (liquid water) at the Earth's surface despite a reduced solar luminosity in the past (Schwarzschild, 1958), the so-called "faint young sun paradox" (Ulrich, 1975).

Noble gases are chemically inert elements that are powerful tracers of the formation and subsequent evolution of the Earth's atmosphere. Xenon (Xe), the heaviest stable noble gas, has nine isotopes that present mass-dependent isotope variations. Some Xe isotopes have also been contributed by extinct ( $^{129}I$ ,  $T_{1/2} = 15.7$  Ma;  $^{244}Pu$ ,  $T_{1/2} = 82$  Ma) and extant ( $^{238}U$ ,  $T_{1/2} = 4.47$  Ga) radioactive nuclides. Terrestrial atmospheric Xe has two unique features. First, atmospheric Xe is depleted by a factor of 20 compared to the Ar/Kr/Xe elemental pattern defined by chondrites (e.g., Pepin (1991)). Second, atmospheric xenon is strongly enriched in heavy relative to light isotopes with a mass-dependent fractionation of 30–40‰  $u^{-1}$  (computed from light isotopes which are devoid of radioactive nuclide contribution) compared to other known solar system components such as AVCC-Xe (Average Carbonaceous Chondrite Xe) or SW-Xe (Solar Wind Xe) (Ott, 2014). These two features form the "xenon paradox" (Ozima and Podosek, 2002).

An additional striking feature of atmospheric Xe is that it cannot be directly related to either chondritic Xe or solar Xe. When corrected for mass-dependent isotope fractionation, the heavy Xe isotopes  $^{134}Xe$  and  $^{136}Xe$  are depleted

relative to both Solar and Chondritic signatures (Pepin, 1991). This is a problematic issue since no known nuclear process can selectively decrease the abundance of these isotopes in the atmosphere. Furthermore, spontaneous fission of extinct  $^{244}Pu$  ( $T_{1/2} = 82$  Ma) and extant  $^{238}U$  ( $T_{1/2} = 4.47$  Ga), which produce the heavy isotopes of Xe in the silicate Earth, would have increased levels of  $^{134}Xe$  and  $^{136}Xe$  in the atmosphere with time due to mantle and crustal degassing, making the imbalance even more severe. An alternative and mathematically-derived initial Xe component, labeled U-Xe, has thus been defined in previous studies (Takaoka, 1972; Pepin, 1991) and is considered as the starting isotopic composition for the Earth's atmosphere. Recent results obtained on 3.3 Ga-old samples from the Barberton Greenstone Belt (South Africa) demonstrated the existence of the U-Xe early in Earth's history (Avice et al., 2017). Finally, after decades of unsuccessful searching for this component, recent measurements of the isotopic composition of Xe in the coma of comet 67P/Churyumov-Gerasimenko revealed that the progenitor of atmospheric Xe, the U-Xe, reflects a mix between about 22% of cometary Xe (strongly depleted in  $^{134}Xe$  and  $^{136}Xe$ ) and 78% chondritic Xe (Marty et al., 2017).

Even assuming U-Xe as the starting isotopic composition for the atmosphere, solving the xenon paradox calls for complex models with episodes of mantle degassing and early isotopic fractionation of atmospheric noble gases driven by hydrodynamic escape of hydrogen (Pepin, 1991), and/or late addition of cometary gases to a residual, fractionated atmosphere (Dauphas, 2003). In these models, Xe processing and fractionation occurred during the earliest stages of terrestrial accretion (see a review by Dauphas and Morbidelli, 2014). Some recent studies call these models into question and propose instead that the depletion and isotopic fractionation of Xe took place progressively during geological eons. This model is based on the analysis of xenon in ancient rocks (Srinivasan, 1976; Pujol et al., 2009; Pujol et al., 2011; Avice et al., 2017; Bekaert et al., 2018) or in ancient fluids (Holland et al., 2013; Warr et al., 2018) that reveal a stable isotope composition of xenon intermediate between those of the potential cosmochemical ancestors and of the modern atmosphere. Pujol et al. (2011) proposed that the isotope fractionation of atmospheric xenon was a long-term process that was still active during the Archean eon. This fractionation has to be specific to Xe, since other noble gases do not appear to have been fractionated. Because xenon is the heaviest noble gas, only non-thermal escape of this element would have been possible, perhaps related to its specific electronic structure, which makes it more prone to ionization by solar UV photons than other noble gases. These results have thus been subsequently interpreted as an evidence for a continuous

Download English Version:

<https://daneshyari.com/en/article/8910726>

Download Persian Version:

<https://daneshyari.com/article/8910726>

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