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Xenon isotope systematics, giant impacts, and mantle degassing on the early Earth

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Abstract

The relationships between the major terrestrial volatile reservoirs are explored by resolving the different components in the Xe isotope signatures displayed by Harding County and Caroline CO_2 well gases and mid-ocean ridge basalts (MORB). For the nonradiogenic isotopes, there is evidence for the presence of components enhanced in the light $^{124-128}Xe/^{130}Xe$ isotope ratios with respect to the terrestrial atmosphere. The observation of small but significant elevations of these ratios in the MORB and well gas reservoirs means that the nonradiogenic Xe in the atmosphere cannot be the primordial base composition in the mantle. The presence of solar-like components, for example U–Xe, solar wind Xe, or both, is required.

For radiogenic Xe generated by decay of short-lived ^{129}I and ^{244}Pu, the $^{129}Xe_{rad}/^{136}Xe_{244}$ ratios are indistinguishable in MORB and the present atmosphere, but differ by approximately an order of magnitude between the MORB and well gas sources. Correspondence of these ratios in MORB and the atmosphere within the relatively small uncertainties found here significantly constrains possible mantle degassing scenarios. The widely held view that substantial early degassing of $^{129}Xe_{rad}$ and $^{136}Xe_{244}$ from the MORB reservoir to the atmosphere occurred and then ended while ^{129}I was still alive is incompatible with equal ratios, and so is not a possible explanation for observed elevations of $^{129}Xe/^{130}Xe$ in MORB compared to the atmosphere. Detailed degassing chronologies constructed from the isotopic composition of MORB Xe are therefore questionable.

If the present estimate for the uranium/iodine ratio in the bulk silicate Earth (BSE) is taken to apply to all interior volatile reservoirs, the differing $^{129}Xe_{rad}/^{136}Xe_{244}$ ratios in MORB and the well gases point to two episodes of major mantle degassing, presumably driven by giant impacts, respectively ~20–50 Ma and ~95–100 Ma after solar system origin assuming current values for initial $^{129}I/^{127}I$ and $^{244}Pu/^{238}U$. The earlier time range, for degassing of the well gas source, spans Hf–W calculations for the timing of a moon-forming impact. The second, later impact further outgassed the upper mantle and MORB source. A single event that degassed both the MORB and gas well reservoirs at the time of the moon-forming collision would be compatible with their distinct $^{129}Xe_{rad}/^{136}Xe_{244}$ ratios only if the post-impact iodine abundance in the MORB reservoir was about an order of magnitude lower than current estimates. In either case, such late dates require large early losses of noble gases, so that initial inventories acquired throughout the Earth must have been substantially higher.

The much larger $^{129}Xe_{rad}/^{136}Xe_{244}$ ratio in the well gases compared to MORB requires that these two Xe components evolve from separate interior reservoirs that have been effectively isolated from each other for most of the age of the planet, but are now seen within the upper mantle. These reservoirs have maintained distinct Xe isotope signatures despite having similar Ne isotope compositions that reflect similar degassing histories. This suggests that the light noble gas and radiogenic Xe isotopes are decoupled, with separate long-term storage of the latter. However, without data on the extent of heterogeneities within the upper

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mantle, this conclusion cannot be easily reconciled with geophysical observations without significant re-evaluation of present noble gas models. Nevertheless the analytic evidence that two different values of $^{129}Xe_{rad}/^{136}Xe_{244}$ exist in the Earth appears firm. If the uranium/iodine ratio is approximately uniform throughout the BSE, it follows that degassing events from separate reservoirs at different times are recorded in the currently available terrestrial Xe data.

Keywords: xenon; radionuclide daughters; mantle; atmosphere; moon; giant impacts; degassing

1. Introduction

There is strong evidence from dynamical modeling that Earth was impacted by massive bodies in the Mercury–Mars size range during its accretion, and that the moon formed from debris ejected by one of these collisions [1–3]. Such impacts likely powered degassing of volatiles from the Earth's interior, and escape of atmospheric gases to space, and so were key events in shaping the present atmosphere. Clues to the timing and extent of early noble gas losses are recorded in the abundances of xenon isotopes produced by two extinct radionuclides, $^{129}Xe_{rad}$ from β decay of ^{129}I ($\tau_{1/2}$= 15.7 Ma) and $^{131-136}Xe_{244}$ from spontaneous fission of ^{244}Pu ($\tau_{1/2}$=80.0 Ma). Amounts of $^{129}Xe_{rad}$ on Earth are much smaller than the amounts of parent ^{129}I in Earth-forming materials 4567 Ma ago, pointing to substantial losses of Xe and other volatiles during planet formation. One challenge has been to assess the effects of these losses on the initial volatile inventories and present-day compositions in different terrestrial reservoirs. Another has been to determine the times when the reservoirs were depleted [4–9] and their relation to the timing of giant impacts on Earth estimated from other evidence, e.g. Hf–W isotope systematics [10–15].

Xenon data from Earth's volatile reservoirs are evaluated here as mixtures of components acquired during accretion and generated on and in the planet by fractionation and radioactive decay. Discussion is focused primarily on calculated ratios of radiogenic ^{129}Xe to plutogenic ^{136}Xe in the atmosphere and in mantle Xe reservoirs, and on what their similarities or differences imply for reservoir interrelations and their geophysical and geochemical environments. These ratios are also used to obtain Xe–Xe "closure age" approximations of when the reservoirs began to retain daughter Xe isotopes after episodes of major volatile loss. Closure age estimates are useful in relating the results of this work to calculations of the timing of differentiation events in the early Earth and to the literature on terrestrial noble gas distributions, much of which is directed toward derivation of degassing chronologies.

The following analyses of the data reveal evidence for the presence of a mantle Xe component that is isotopically related to Xe in the sun and meteorites. Further, the relative proportions of radiogenic ^{129}Xe to plutogenic ^{136}Xe are essentially identical in the upper mantle and atmosphere but differ greatly from another interior reservoir. These results identify new and potentially powerful constraints on the origins and affiliations of mantle and atmospheric noble gases.

2. Data evaluation methods

2.1. Resolving daughter Xe isotopes in the atmosphere

Obtaining Xe isotopic constraints on relationships between the various terrestrial reservoirs, as well as the extent and timing of volatile losses, has been hampered by difficulties in resolving daughter Xe isotopes from nonradiogenic Xe. Contributions from ^{129}I and ^{244}Pu must be separated from an underlying nonradiogenic base composition. However, there is no common solar system Xe component that can provide a suitable atmospheric base. The composition used here is U–Xe, a component derived from comparison of terrestrial and meteorite data [16]. Hydrodynamic escape to space, driven by energy deposited in a giant impact or by strong ultraviolet radiation from the young sun, dissipates and isotopically fractionates a primordial atmosphere containing U–Xe [9,16–18]. The result is a fractionated U–Xe residue called "Nonradiogenic Earth Atmosphere" or NEA-Xe, to which decay products were later added [16–18] and are now clearly resolvable.

2.2. Resolving mantle Xe components

For the mantle, degassing histories are deduced from Xe found in MORB, crustal CO_2 well gases that have trapped mantle volatiles, and ocean island basalts (OIB). Despite pervasive atmospheric (Air-Xe) contamination [19–22], $^{129}Xe_{rad}$ is readily discernible, most clearly in MORB and well gases. However, plutonium-derived Xe is obscured by the masking presence of abundant heavy isotope Xe generated by fission of long-lived uranium-