ORIGIN OF RARE GASES IN THE TERRESTRIAL ATMOSPHERE AND PLANETARY COMPARISONS; D. Porcelli and G. J. Wasserburg, The Lunatic Asylum, California Institute of Technology, Pasadena, CA 91125

We have previously presented a model for the distribution and transport of rare gases within the Earth [1,2,3,4] which explains the available observational data for mantle He, Ne, Ar, and Xe isotope compositions and provides specific predictions regarding the rare gas isotopic compositions of the lower mantle, interactions between rare gas reservoirs, and mantle rare gas concentrations. Here we discuss the constraints on the acquisition and evolution of atmospheric rare gases that are derived from this model, and show that these constraints are compatible with planetary evolution processes put forth by others. Early losses of rare gases has occurred on both the Earth and Mars, and a late atmosphere was added to the Earth by accretion of gas-rich materials. Both atmospheres have suffered loss of rare gases, causing elemental and isotopic fractionation, as well as small additions by outgassing of the planetary interior. These processes are reflected in the relationship between the atmospheric and interior rare gases of both planets.

The model for the Earth has two mantle reservoirs, an approximately closed system lower mantle and a highly depleted upper mantle that is open to interactions with the lower mantle by mass transport and atmosphere. It is assumed that rare gases in the upper mantle are derived from the mixing of three components: rare gases from the lower mantle, subducted rare gases, and radiogenic nuclides produced in situ over a residence time of ~1.4Ga. The concentration of each rare gas isotope in the upper mantle is assumed to be in steady state. From the available data regarding the present composition of the upper mantle and the production of ^{4}He, ^{21}Ne, ^{40}Ar, and ^{136}Xe in the upper mantle through decay of ^{40}K, ^{238}U, and ^{232}Th, constraints are obtained on the composition of the lower mantle rare gas component. The lower mantle is assumed to have evolved as a closed system over ~4.5Ga, and has been subject to isotopic shifts from initial values due to decay of ^{40}K, ^{238}U, ^{232}Th, ^{129}I, and ^{244}Pu. Concentrations of nonradiogenic rare gases in the lower mantle are calculated from the concentrations of parent elements and the constraints on the present isotopic compositions. For isotopes that are not presently generated in the mantle, isotopic variations are attributed to only mixing of atmospheric rare gases and lower mantle rare gases. For example, the upper mantle ^{129}Xe/^{130}Xe ratio is greater than that of the atmosphere[5], and so the lower mantle ratio is constrained to be equal to, or greater than, the upper mantle ratio and more radiogenic than atmospheric Xe.

The model treats the atmosphere as a separate reservoir with rare gas isotope compositions that are distinct from those in the mantle and makes no initial assumptions regarding its origin. This differs from the approach of earlier models of mantle rare gas isotope evolution [6] which assumes that the atmosphere was formed by degassing of the upper mantle. In their model, rare gases presently in the upper mantle are then residual to this degassing, with isotopic compositions that reflect the integrated history of degassing and grow-in of radiogenic isotopes. Furthermore, the lower mantle is assumed to have isotopic compositions equal to those of the atmosphere. Other workers have argued that losses of atmospheric rare gases by hydrodynamic escape is the cause of the fractionation of nonradiogenic Xe isotope compositions [7,8] and possibly of Ne isotopes [9] relative to anticipated rare gas sources. Late additions of gas-rich material have also been invoked [e.g.11,12]. These processes of open system behavior are incompatible with simple models of a closed system Earth.

The present model has direct consequences for the evolution of the terrestrial atmosphere and its relation to rare gases retained in the lower mantle:

1. The atmosphere is derived from a rare gas reservoir with distinct radiogenic isotope characteristics and which is no longer represented in the Earth. Xe that has been preserved in the lower mantle since early Earth history has ^{129}Xe/^{130}Xe and ^{136}Xe/^{130}Xe ratios that is more radiogenic than those of the atmosphere, and represents a reservoir with greater I/Xe and Pu/Xe ratios than the source of the atmosphere.
2. The atmosphere has suffered early losses of radiogenic ^{129}Xe and ^{136}Xe [13,14] that was necessarily accompanied by loss of nonradiogenic Xe. This has occurred over timescales of ~10^{8}yrs. Lower mantle Xe has also suffered losses on a timescale similar to that of the atmosphere [3]. These loses may have been due to the effects of impact of a Mars-size body to form the moon [15,16]. Alternatively, this may reflect accretional losses during late accretion of the Earth. The coincidence of the timescale of these losses with the young ^{207}Pb-^{206}Pb age of the Earth and moon [17,18] suggests that Pb/U fractionation may have also been occurring during these events.
3. Subsequent to these losses, the nonradiogenic atmospheric rare gases were added by late accretion. The source of these gases is constrained to be more gas-rich than the lower mantle and CI chondrites, as these sources have isotope characteristics that are too radiogenic.

4. The fractionation of atmospheric Xe isotopes relative to other solar system compositions is either inherited from the gas-rich sources or due to subsequent gas loss from the Earth [see 7].
5. Rare gases produced in the upper mantle by decay subsequent to 4.45Ga and outgassed are sufficient to produce the radiogenic ^{129}Xe and ^{136}Xe in the atmosphere. The present atmospheric isotope compositions reflect the ratio of this input to the late-accreted nonradiogenic nuclides that dominate the atmosphere.
6. The lower mantle has rare gases with nonradiogenic isotope compositions and relative abundances that are distinct from those of the atmosphere and which are comparable to solar system compositions. The lower mantle light rare gases that are solar in composition. It is likely has a higher Xe/Ar ratio that is similar to CI chondrites. Also, it is possible that lower mantle Xe is close in composition to solar Xe; lack of evidence in mantle-derived materials for such a composition may be due to subduction of Xe into the upper mantle and/or atmospheric contamination of samples.

The above conclusions regarding the evolution of the terrestrial atmosphere are compatible with current understanding of planetary processes. Comparisons can also be drawn with the rare gas systematics of Mars. Martian atmospheric abundances are known from direct measurements of rare gases in the atmosphere by Viking [19,20]. From the low abundance of rare gases found in the atmosphere, Mars was seen as deficient in atmophile elements [21]. It is widely believed that SNC meteorites are derived from Mars and carry trapped Martian atmospheric gases, based on measured rare gas and N measurements [22,23]. Measurements of SNC meteorites have obtained precise determinations of the isotopic compositions of Martian atmospheric rare gases [24,25]. Pepin [7,8] and Zahnle [27] have reviewed the Martian data and possible evolutionary processes. From trace element data from these meteorites, it has been argued that Mars is volatile-rich [26]. The depletion of atmophile elements then indicates that substantial atmospheric loss has occurred, and this is indicated by N isotope data [19]. Xe isotopes are fractionated with respect to solar or CI chondrite Xe compositions, and this has been attributed to fractionation during loss from the atmosphere by hydrodynamic escape [7,8]. These losses have resulted in a decoupling of the current atmosphere from the interior.

Rare gases in SNC meteorites define correlations that appear to be the result of mixing of at least two components [25]. One is identified with the Martian atmosphere based on similarities with Viking measurements. The other has been interpreted as reflecting a separate, interior reservoir. This component is most represented in the meteorite Chassigny [25] and has a solar Xe isotope composition and a higher Xe/Ar ratio than the Martian atmosphere. The Xe in the Martian atmosphere and the Martian interior are not related in a simple way. The atmosphere appears to have a substantially higher ratio of radiogenic ^{129}Xe to ^{130}Xe than the interior and requires separate evolution of the two reservoirs since early in Martian history. It has been suggested that the difference in I/Xe between the reservoirs is due to losses of ^{130}Xe from the atmosphere while I remains in the crust [18,19]. Subsequent decay of ^{129}I and outgassing of radiogenic ^{129}Xe would then have a large effect on the isotopic composition of the atmosphere. Although the Martian atmosphere is highly depleted in Xe, it contains a substantial proportion of radiogenic ^{129}Xe. It is likely that early losses of radiogenic ^{129}Xe have occurred [8,18], although a precise calculation of the timescales of early loss is not possible. Although Pu-derived fissiogenic Xe is expected to accompany radiogenic ^{129}Xe, it appears to be absent from the Martian atmosphere [24,27] and the reason for this is unknown. While Xe in the Martian atmosphere is more radiogenic than the planetary interior, terrestrial atmospheric Xe is less radiogenic than Xe in the Earth's mantle. In the context of our model of terrestrial rare gases, this is due to differing proportions of late-accreted nonradiogenic rare gases to outgassed radiogenic ^{129}Xe in the two planets.

In summary, early losses of rare gases have occurred from both planets. Late accretion of gas-rich material has supplied volatiles to the terrestrial atmosphere. Both atmospheres have evolved by losses that have caused isotopic and elemental fractionations, as well as by additions of radiogenic nuclides from the interior. Other workers have discussed these atmospheric evolution processes in the context of planetary evolution; we have shown that these processes are compatible with the evidence for terrestrial mantle rare gases.

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