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Deep Mantle Rare Gases and Early Earth History

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There have been many hypotheses regarding the source of rare gases and other volatiles in the Earth's atmosphere. Fewer models consider the origin of rare gases still within the Earth's mantle. Here the relevant constraints are outlined, along with the implications for rare gas acquisition mechanisms.

1. It has been long established that atmospheric Xe contains ^{129}Xe from short-lived ^{129}I, and ^{136}Xe from short-lived ^{244}Pu. Xe isotope systematics indicate that there were substantial losses of these daughter nuclides over the first 100 Ma (Pepin and Phinney, 1976). MORB exhibit enrichments in ^{129}Xe and ^{136}Xe relative to the atmosphere. A significant proportion of this excess ^{136}Xe appears due to ^{244}Pu (rather than ^{238}U) (Kunz et al., 1998, Porcelli and Wasserburg, 1995). This mantle Xe cannot be related to the atmosphere by degassing (Ozima et al., 1985), and therefore is from the deep mantle. This reservoir also suffered substantial early losses. Calculations for a single catastrophic degassing event indicate that losses of >90% occurred as late as 100 Ma from both the deep mantle and atmosphere. Losses from the latter may have been somewhat less or earlier. Such losses of rare gases from the interior have not been considered previously.

2. Closed system calculations for He isotopes provide minimum initial concentrations of deep mantle rare gases. If mantle Xe is derived from the He-rich deep mantle, then these calculated concentrations are for after the extensive Xe losses. The calculated loss factor applies to all the rare gases, so 100 times more rare gases were incorporated into the solid Earth initially than calculated from He isotopes. Such concentrations have not been considered previously in models of terrestrial volatile incorporation.

3. Accreting carrier phases likely suffered substantial losses to space during early heating and differentiation, and to the terrestrial atmosphere during impact and subsequent melting. If these materials contributed to the interior of the Earth, their initial, trapped concentrations must have been high enough to sustain such losses and still provide the initial terrestrial concentrations deduced from He and Xe systematics.

4. Ne trapped within the Earth is solar, and Ar and Xe may be as well.

5. While atmospheric Xe has been strongly fractionated relative to other solar system compositions, it is not clear if deep mantle Xe has been. Although upper mantle nonradiogenic Xe appears to be similar to that of the atmosphere, there is the possibility of substantial subduction of atmospheric Xe into the upper mantle, thereby masking deep mantle Xe characteristics.

Few mechanisms of rare gas incorporation can provide an explanation for the high initial deep Earth concentrations of solar gases, especially in the high-energy environment of planetary accretion. It is particularly problematic to find carrier phases that can supply such concentrations directly into the Earth. One mechanism that does satisfy the above constraints involves the gravitational capture of gases from the solar nebula (Mizuno et al., 1980). If a significant proportion of the Earth is accreted prior to dispersal of the nebula, an atmosphere of solar gases will be attracted that will have a strong blanketing effect. Melting of the underlying Earth will occur due to accretional energy, and solar rare gases from the atmosphere will be dissolved and advected into the deep mantle. Atmospheric conditions that maintain sufficiently high surface atmospheric pressures (to dissolve enough gases) and sufficiently high temperatures (to melt down to the deep mantle) can be achieved.

The cataclysmic giant-impact proposed for moon formation can explain the inferred substantial and late gas losses. Such an event naturally accounts for losses of rare gases from the deep mantle as well as from the atmosphere. The overall constraints on the timing of moon formation are consistent with the Xe isotope constraints for gas loss. In this case, radiogenic isotopes produced in the first ~100 Ma were lost either directly to space or into a massive atmosphere. This would have been followed by fractionating losses from the atmosphere to space that established the present nonradiogenic Xe isotope atmospheric composition (Pepin, 1997). Subsequent degassing of radiogenic Xe from the upper portion of the silicate Earth into the atmosphere provided the atmospheric radiogenic Xe budget.

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