Xenon Fractionation, Hydrogen Escape, and the Oxidation of the Earth

Xenon in Earth's atmosphere is severely mass fractionated and depleted compared to any plausible solar system source material, yet Kr is unfractionated. These observations seem to imply that Xe has escaped from Earth. But to date no process has been identified that can cause Xe, which is heavier than Kr, to escape while Kr does not. Vigorous hydrodynamic hydrogen escape can produce mass fractionation in heavy gases (Hunten et al. 1987, Sasaki & Nakazawa 1988, Pepin 1991). The required hydrogen flux is very high but within the possible range permitted by solar Extreme Ultraviolet radiation (EUV, which here means radiation at wavelengths short enough to be absorbed efficiently by hydrogen) heating when Earth was on the order of 100 Myrs old or younger. However this model cannot explain why Xe escapes but Kr does not.

Recently, what appears to be ancient atmospheric xenon has been recovered from several very ancient (3-3.5 Ga) terrestrial hydrothermal barites and cherts (Pujol 2011, 2013). What is eye-catching about this ancient Xe is that it is less fractionated that Xe in modern air. In other words, it appears that a process was active on Earth some 3 to 3.5 billion years ago that caused xenon to fractionate. By this time the Sun was no longer the EUV source that it used to. If xenon was being fractionated by escape — currently the only viable hypothesis — it had to be in the less unfamiliar context of Earth's Archean atmosphere and under rather modest levels of EUV forcing. This requires a new model.

Here we address rthe circumstances in which Xe, but not Kr, could escape from Earth as an ion. In a hydrodynamically escaping hydrogen wind the hydrogen is partially photo-ionized. The key concepts are that ions are much more strongly coupled to the escaping flow than are neutrals (so that a relatively modest flow of H and H+ to space could carry Xe+ along with it), and that xenon alone among the noble gases is more easily ionized than hydrogen. This sort of escape is possible if not prevented by a planetary magnetic field. The best prospects for Earth are therefore escape along the polar field lines, although a very weak or absent magnetic field would likely work as well. As applied to the Archean Earth the discussion will be constrained by diffusion-limited hydrogen escape. The extended history of hydrogen escape implicit in Xe escape in the Archean is consistent with suggestions that hydrogen escape from the anoxic Archean atmosphere was considerable, because biogenic methane is expected to have been rather abundant. Hydrogen escape plausibly played the key role in creating oxidizing condition at the surface of the Earth and setting the stage for the creation of an O2 atmosphere (Urey 1951, Hunten and Donahue 1976, Catling et al 2001, Zahnle et al 2013).

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