XENON FRACTIONATION AND ARCHEAN HYDROGEN ESCAPE. II. NOW MORE THAN EVER.

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Introduction: Xenon is the heaviest gas found in natural planetary atmospheres, yet there is more evidence that Xe escaped from Earth than for any element heavier than helium. (1) Most of the radiogenic Xe from the decay of ^{129}I (half-life 15.7 Myr) and ^{244}Pu (half-life 81 Myr) that is Earth's cosmic birthright is missing. (2) The nonradiogenic isotopes of xenon in air are strongly mass fractionated compared to any known solar system source (Figure 1), to a degree on the order of 4% per atomic mass unit (amu). By contrast the lighter Kr may not be fractionated at all [1]. (3) Nonradiogenic Xe is also underabundant relative to Kr, when compared to chondrites, by a factor in the range of 4-20 depending on which chondrites one is comparing to. Points 2 and 3 – Figure 1 – imply that Xe has been subject to fractionating escape and Kr not.

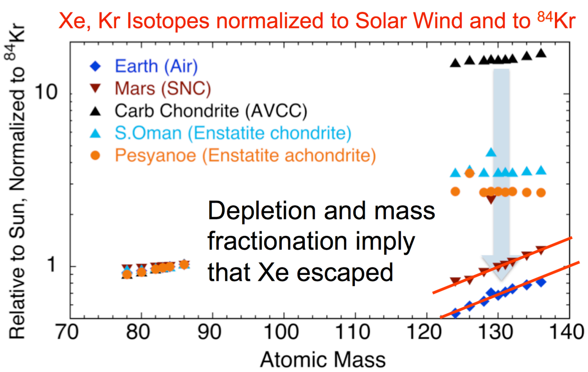

Figure 1. Xenon's depletion and fractionation imply that Xe has escaped from Earth and Mars. Here isotopic abundances are normalized to ^{84}Kr. "AVCC" denotes average carbonaceous chondrites [2]. Mars is from SNCs, Solar Wind from *Genesis* [3].

The original Xe in Earth's atmosphere is indeed Pepin's U-Xe. Xenon in air has been augmented by decay of ^{129}I and ^{244}Pu, and it has been smoothly mass fractionated. Pepin also treated the difference between AVCC Xe and Solar Xe as an independent primordial Xe component. With these accounted for (Figure 2), Earth's original atmospheric Xe – called U-Xe – is revealed to be depleted in heavy isotopes to the same degree that AVCC are enriched [1,2]. Until *Rosetta* sampled 67P/CG, U-Xe was unique in the Solar System. It now appears that Pepin was mostly right: U-Xe and Solar Xe can be made by mixing different proportions of cometary and chondritic xenons, with Earth about twice as rich in cometary Xe as the Sun [4].

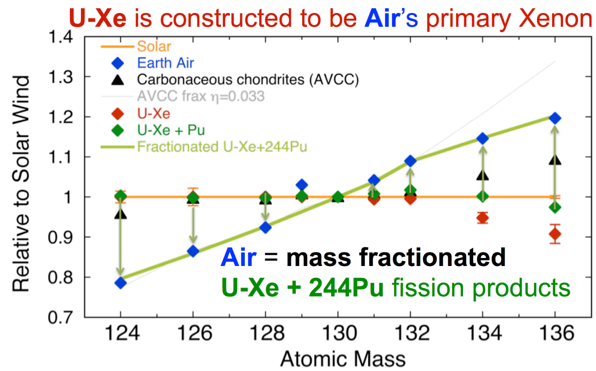

Figure 2. Pepin [1,2] reconstructed U-Xe from atmospheric Xe by correcting for the mass fractionation, removing the fissiogenic Xe from ^{244}Pu, and requiring that U-Xe, Solar Xe, and AVCC Xe comprise different proportions of two end member compositions that differ in the abundances of the heavy isotopes.

Xenon trapped in Archean rocks reveals that xenon's fractionation grew over the first half of Earth's history, reaching modern values ca 2 Ga [5,6]. Evidently Xe was fractionated by a process that took place on Archean Earth. Figure 3 shows some exemplary Archean data. The full suite of data [6] are plotted in summary form in Figure 4, where we have compared xenon's story to oxygen's and sulfur's. That Xe should be a proxy for the changing redox composition of Earth's atmosphere would seem unlikely but for the fact that Xe cannot escape on its own – it needs to be dragged to space by hydrogen, and thus the evolution of xenon's isotopes is tied to hydrogen escape and therefore to how much hydrogen (or methane) was in the atmosphere. The hydrogen escape is in turn linked to the oxygenation of the Earth [7].

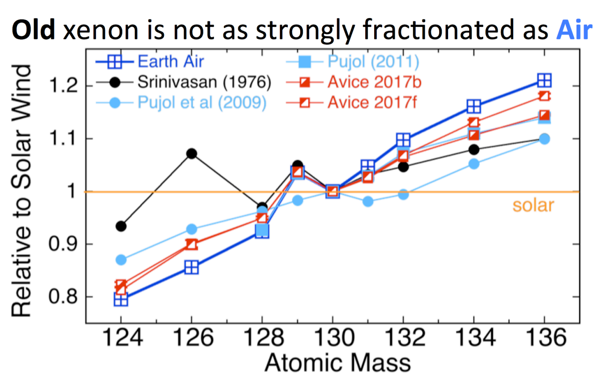

Figure 3. Xenon trapped in Archean rocks [5.6] is less fractionated than modern air. Evidently Xe was escaping from Earth during the Archean.

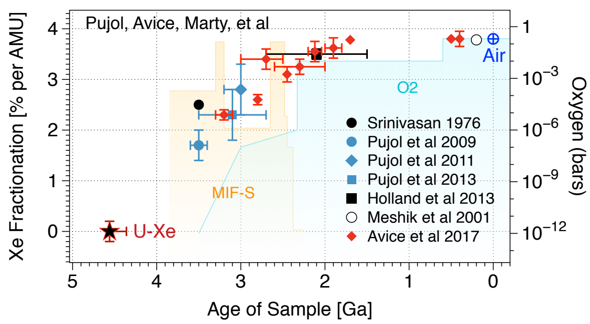

Figure 4. The history of xenon mass fractionation on Earth compared to the histories of mass-independent fractionation of sulfur and to the the inferred history of oxygen on Earth. Adapted from [7].

Xenon alone among the noble gases can escape from planetary atmospheres as an ion. This is possible in hydrodynamic hydrogen escape because the hydrogen is partly ionized by incident solar XUV, provided that H^+ can also escape, as will happen in the absence of a magnetic field or, if the planetary magnetic field is strong, along open field lines as a polar wind. The strong Coulomb interaction between Xe^+ and H^+ is what makes this possible. Xenon should be ionized because it is more easily ionized (12.1 eV) than H (13.6 eV, $\lambda < 91$ nm). By contrast Kr (14.0 eV) is more difficult to ionize than H. Thus Kr remains neutral.

We construct a simple model of hydrodynamic hydrogen escapes from a static CO2 atmosphere. The model accounts for radiative heating and radiative cooling, diffusive separation and eddy mixing, dissociation and ionization of hydrogen, transonic acceleration, and the hydrodunamic drag on Xe^+ and the neutral noble gases. The model solves for the required XUV irradiation by shooting from the lower boundary holding the hydrogen escape flux fixed. Xe^+ escape is also solved by shooting, but the possibility of escape can be assessed at a glance by examining the crossover mass, which is the mass below which a species is dragged to space [7]. The process as described is strongly mass fractionating. A particular example is shown in Figure 5.

The shooting model is swift enough to pave over a parameter space, as in Figure 6. The crimson realm of lost Xe is kingdom of possibilities rather than certainties: Xe+ escape is possible, but we have neglected Xe recombination, which means that Xe escape would not be as efficient as we have computed. Neutrals begin to escape for XUV > 100 and abundant hydrogen. The empty quarter to the lower right can be filled only by allowing CO_2 or its dissociation products to escape, which we have not modeled here.

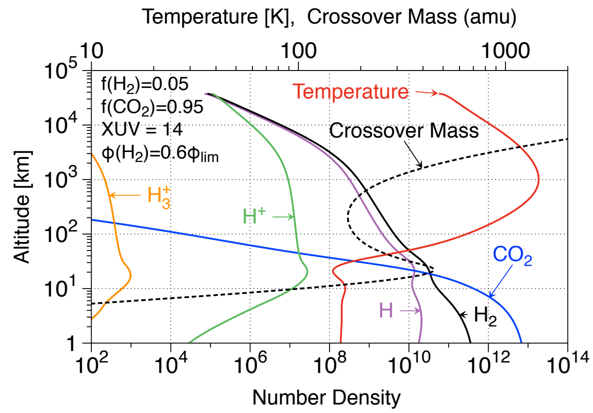

Figure 5. An exemplary case where Xe^+ escape is possible, as indicated by the crossover mass, which is always greater than the mass of a Xe^+ ion save near the homopause. In this example the Solar XUV flux is 14X present and the hydrogen mixing ratio is 5% (the equivalent CH_4 mixing ratio in the lower atmosphere is 2.5%). The partially dissociated and partially ionized hydrogen diffuses through a static but inflated CO_2 atmosphere; once the radiative cooling by CO_2 is left behind the hydrogen becomes hot and accelerates into space hydrodynamically.

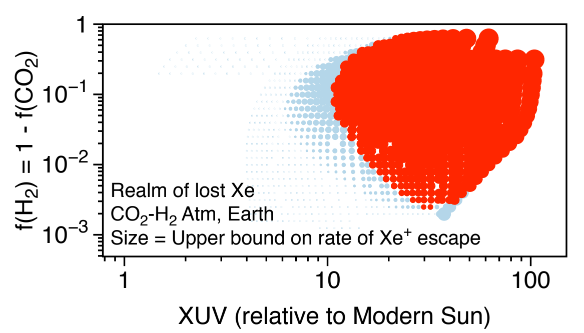

Figure 6. Conditions where Xe^+ can escape from ancient Earth are marked in red (with less favorable chances in blue). Two factors play a role: the atmosphere needs to contain a lot of hydrogen (either H_2 or CH_4 will do), and the Sun needs to be a much stronger source of XUV radiation than it is now; the latter has been surmised from stellar analogs for several decades. For Xe to escape, the Archean atmosphere must have contained by volume about 1% CH_4 or H_2 or both.

References: [1] Pepin (2006) EPSL 252, 1-14. [2] Pepin (1991) Icarus 92, 2-79. [3] Meshik et al (2014) GCA 127, 326-347. [4] Marty et al (2017) Science 356, 1069-1072. [5] Pujol M. et al (2011) EPSL 308, 298-306. [6] Avice et al (2017) GCA. [7] Hunten et al (1987) Icarus 69, 532-549.