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Discontinuous isotopic evolution of paleo-atmospheric xenon: A record of Sun-Earth interactions in the deep time?

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The terrestrial atmosphere evolved through time due to exchanges between Earth reservoirs, and by volatile escape to space. Paleo-atmospheric gases trapped in ancient mineral phases shows that the noble gas (Ne-Ar-Kr) and N_2 isotopic compositions of the Archean atmosphere have not evolved significantly since 3.5 Ga. In contrast, the isotopic composition of paleo-atmospheric Xe gradually changed during the first ~ 2Gyr of Earth history to reach its modern, fractionated composition (Avice et al GCA 232, 82, 2018). Two recent studies from the CRPG-Nancy group suggest that (i) this Xe isotope evolution was not continuous but presented stepwise change around ~2.7 Ga (Almayrac et al Chem Geol 581, 120405, 2021), and (ii) the end of its evolution was synchronous with the great oxidation event at 2.4 Ga (Ardoin et al GPL, in press, 2022). Xenon is the easiest of the noble gas species to be ionized. Models propose trapping Xe in organic haze as a cause of isotope fractionation, but this still requires an escape mechanism to lose Xe to space (Hébrard and Marty EPSL 385, 40, 2014) or hydrodynamic entrainment of heavy Xe+ ions by escaping H+ (Zahnle et al GCA 244, 56, 2019). Both require contribution of a younger Sun to provide energy in the UV-XUV range, and studies of star analogues suggest that, depending on the rotational velocity, the energy outflow driven by photons and solar wind ions could have varied by orders of magnitude (Tu et al AA 577, L3, 2015; Güdel, SSR 216, 143, 2020), with a lower limit around ~10 times the modern solar regime. Solar flare events could have also been orders of magnitude more intense than at present, and we postulate that abrupt changes occurred in atmospheric Xe isotope fractionation. We propose that extreme solar events plunging deep into the atmosphere at the less magnetically shielded poles, are responsible for short-lived ejection of xenon without affecting other atmospheric species/elements. This specificity is consistent with recent escape modelling. In this sense, paleo-atmospheric Xe isotopes could constitute a unique tracer of Sun-Earth interactions in the deep time.