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# Multi-element constraints on the sources of volatiles to Earth

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We have generated a model tailored to the general formation history of Earth in order to simultaneously estimate sources for H, He, N, Ne, Ar, Kr and Xe. We consider three volatile sources: nebular ingassing, chondrites and comets. Sinks include loss by early hydrodynamic escape and long term loss of ionized Xe. Free variables include: the fraction of ingassed volatiles, the loss of ionized Xe, the type of chondrite (E vs C), the cometary composition and the isotope fractionation during ionized Xe escape. A 10,000 run Monte Carlo simulation generated several hundred solutions that match the abundance of all these elements to within a factor of ~2 of the present-day Earth values, as well as critical isotope ratios ($\delta^{15}N$, $^{20}Ne/^{22}Ne$, $^{36}Ar/^{38}Ar$, Kr and Xe). Chondrite addition is 1-3×$10^{26}$ g and comet addition is 6-9×$10^{21}$ g. The source of volatiles is distinctly different for each element (Fig 1). A large excess of H, He and Ne were supplied by nebular ingassing, with subsequent massive loss (>99% He and Ne) by early hydrodynamic escape. Kr was mostly supplied by comets, Xe was supplied by a mixture of comets and chondrites and N was supplied almost entirely (>98%) by chondrites. $\delta^{15}N$ constraints require a >85% E chondrite source. Kr isotope ratios match measured values of Comet 67P/C-G within error. Xe isotope data can be matched to Earth values using Comet 67P/C-G results, but only by assuming an extreme mass-dependent enrichment factor. Our ingassed H (2.7×$10^{24}$ moles; 3.9×$10^{23}$ as $H_2$ and 2.3×$10^{24}$ as $H_2O$) is equivalent to roughly 17 oceans of water. The late addition H component is at most 10% of the ingassed amount. The D/H ratio of ingassed material requires extreme isotope fractionation during loss to space to explain the present-day Earth values, suggesting loss as atomic H or $H_2$ from $H_2O$ at equilibrium temperatures <300°C.