

MULTI-ELEMENT (H, He, N, Ar, Kr, Xe) CONSTRAINTS ON THE SOURCES OF VOLATILES TO EARTH. Z.D. Sharp¹, P.L. Olson¹ and S. Garai¹, ¹Department of Earth and Planetary Sciences, Northrop Hall, University of New Mexico, Albuquerque, NM 87131, USA, zsharp@unm.edu

Introduction: A number of studies have used one or several isotopic systems to estimate the origin of Earth's volatiles [e.g., 1, 2-7]. In this communication, we generated a model that mimics the presumed formation history of Earth to simultaneously estimate sources for seven volatile elements (H, He, N, Ne, Ar, Kr and Xe). Our model considers four episodes: 1) an ingassing event associated with planetary growth in the presence of a solar nebula. We use ingassing estimates from Olson and Sharp [10]; 2) hydrodynamic escape following dispersal of the nebula. Loss follows a mass-dependent model [11] and is generated to bring He and Ne abundances into agreement with the present-day values; 3) late addition of C and E chondrites and comets. The chondrite and cometary abundances are calculated to match the present-day abundances for these two elements; 4) Long term loss of ionized Xe from polar wind [5, 12].

Our results are controlled by the following six free parameters which are allowed to float in our simulations:

1. Ingassed fraction: varied from 1 to 100% of our previous estimate [10] modified for a presumed solar nebula composition.
2. The proportion of C and E chondrites: varied from 100 % C chondrites to 100% E chondrites.
3. The composition of comets: We consider measured compositions of Comet 67P/C-G [9, 13] and estimates from freezing experiments carried out between 30 and 70 K [8].
4. The comet Xe isotope ratio: We run the model using the measured value from Comet 67P/C-G [13] and an assumed solar ratio [14].
5. The isotopic fractionation associated with hydrodynamic escape of Xe: We treat the mass dependent isotopic fractionation for Xe (the α value) as a free parameter.

6. The isotope fractionation associated with hydrodynamic escape of N, Ne and Ar: For these elements, we would expect that the isotope fractionation during hydrodynamic escape to follow the mass dependency given from step 2 above, but it has been suggested that isotope fractionation between isotopes is negligible[15] for high fluxes during hydrodynamic escape. We therefore N, Ne and Ar to range from zero to the value predicted from equation 1.

A10,000 run Monte Carlo simulation generated several hundred solutions that match the abundance of all these elements to within a factor of ~ 2 (Fig. 1) of the

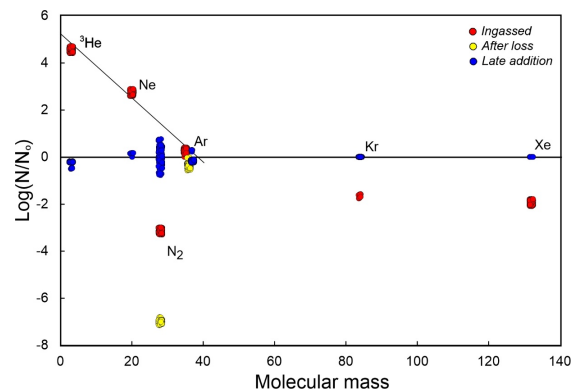


Figure 1. Variations in the volatile abundance vs. molecular mass a number of 'best-fit' simulations. The y-axis is the amount of material relative to the present day abundance of Earth. Red circles are ingassed amounts, yellow circles are post-hydrodynamic escape amounts and blue circles are total following addition from chondrites and comets. Numerous fits satisfy all element abundances.

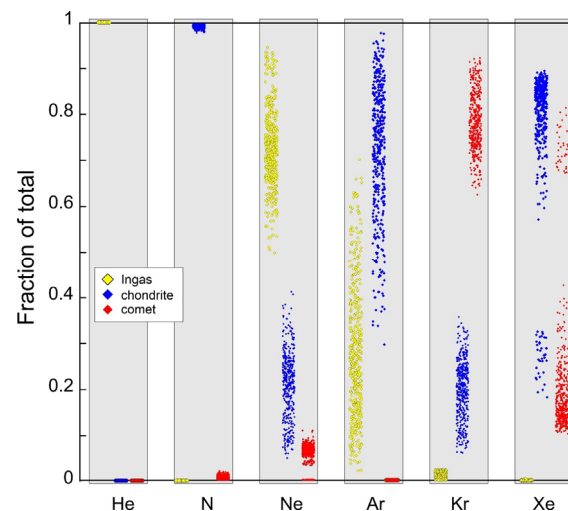


Figure 2. Relative contributions of volatiles from different sources. The vast majority of He and Ne were supplied by ingassing, whereas N was supplied by chondrites. Krypton is supplied by comets and Xe is supplied by a mixture of comets and chondrites. The bimodal fields for Xe are related to the presumed composition of comets, either measured from comet 67P/C-G [9] or estimated from freezing experiments [8].

present-day Earth values, as well as critical isotope ratios ($\delta^{15}\text{N}$, $^{20}\text{Ne}/^{22}\text{Ne}$, $^{36}\text{Ar}/^{38}\text{Ar}$, Kr and Xe). Critically, we find that the sources for these different elements are not the same (Fig. 2). There was a large excess of H, He and Ne supplied by nebular ingassing

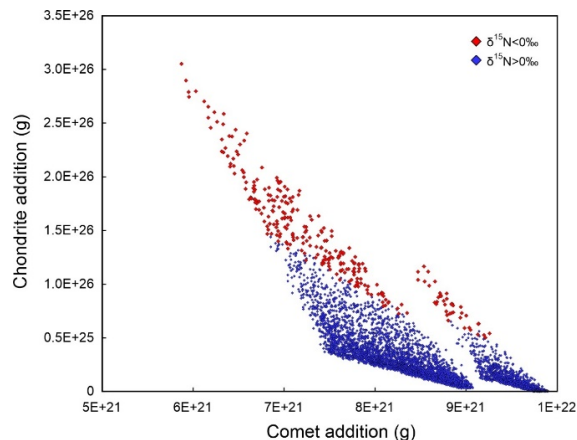


Fig. 3. Chondrite and comet addition estimates from 2000 Monte Carlo simulations. Results with $\delta^{15}\text{N}$ values $<0\text{‰}$ require slightly higher chondritic additions. Two triangular regions are shown. The larger one to the right is generated using freezing point data [8]. The smaller triangle in the lower right is generated using measured cometary composition from comet 67P/C-G [9].

with subsequent massive loss ($>99.99\%$ He and Ne) by early hydrodynamic escape. In contrast to the light noble gases, Kr was mostly supplied by comets, and Xe was supplied by a mixture comets and chondrites. N was supplied almost entirely ($>98\%$) by E chondrites. The source of Ar is mixed, with $\sim 50\%$ comets and the remained from ingassing and chondrite addition. Calculated nitrogen isotope ratio match Earth values with an E chondrite source, but are far too high using a C chondrite source ($>40\text{‰}$ vs AIR) (Fig. 3). The mass of comet and chondrite addition is shown in Fig. 4.

The Kr isotope pattern must follow that of cometary input, given that $>90\%$ of all Kr comes from a comet source. Our results fit the measured values of Comet 67P/C-G within error. Xe isotope data can be matched to Earth values also 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. A large hydrogen isotope fractionation during hydrodynamic escape ($\alpha = 1.6$ to 1.7) is required to explain the present-day D/H values. This α corresponds to equilibrium between H_2 and H_2O at atmosphere temperatures of $\sim 300^\circ\text{C}$. Following H loss, there remain 2 to 4 oceans worth of water on Earth, supplied mostly by nebular ingassing.

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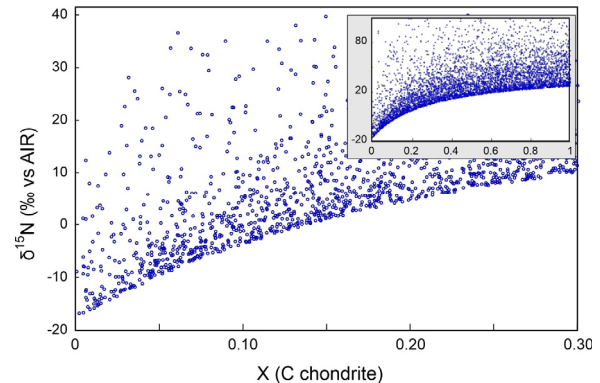


Fig. 4. Calculated $\delta^{15}\text{N}$ values of Earth as a function of the C chondrite fraction to the total chondrite addition (C plus E chondrites). A maximum of 15% C chondrites is permissible to generated a $<0\text{‰}$ $\delta^{15}\text{N}$ value for bulk Earth.

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