

Diversity of oxygen isotope anomaly in the early solar system and the origin

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Oxygen is the third most abundant element in the Solar System and the most abundant element of the terrestrial planets. The presence of oxygen in both gaseous and solid phases makes oxygen isotopes (the terrestrial abundance: $^{16}\text{O} = 99.757\%$, $^{17}\text{O} = 0.038\%$, and $^{18}\text{O} = 0.205\%$) important tracers of various fractionation processes in the solar nebula, which are essential for understanding the evolution of gaseous and solid phases in the early Solar System.

Oxygen isotopic compositions are normally expressed in δ units, which are deviations in part per thousand (permil) in the $^{17}\text{O}/^{16}\text{O}$ and $^{18}\text{O}/^{16}\text{O}$ ratios from Standard Mean Ocean Water (SMOW) with $^{17}\text{O}/^{16}\text{O} = 0.0003829$ and $^{18}\text{O}/^{16}\text{O} = 0.0020052$: $\delta^{17,18}\text{O}_{SMOW} = [(^{17,18}\text{O}/^{16}\text{O})_{sample}/(^{17,18}\text{O}/^{16}\text{O})_{SMOW} - 1] \times 1000$. On a three-isotope diagram of $\delta^{18}\text{O}$ vs. $\delta^{17}\text{O}$, compositions of nearly all terrestrial samples plot along a single line of slope 0.52 called the terrestrial fractionation (TF) line. This line reflects mass-dependent fractionation from a single homogeneous source during chemical and physical processes that results from differences in the masses of the oxygen isotopes. The slope 0.52 results from changes in $^{17}\text{O}/^{16}\text{O}$ that are nearly half those in $^{18}\text{O}/^{16}\text{O}$ because of isotopic mass differences; the precise value of the slope depends on the nature of the isotopic species or isotopologues. In contrast, O-isotopic compositions of the vast majority of extraterrestrial samples, including primitive (chondrites) and differentiated (achondrites) meteorites, deviate from the terrestrial fractionation line, reflecting mass-independent fractionation processes that preceded accretion of these bodies in the protoplanetary disk. Samples from bodies that were largely molten and homogenized such as Earth, Mars and Vesta lie on lines that are parallel to the terrestrial fractionation line. Lunar samples show no detectable deviations from the terrestrial fractionation line.

The largest diversity of mass-independent O-isotopic variations is observed among components of any disequilibrium chondrite. The variations show a result of mass-independent fractionation along a line of slope ~ 1 called carbonaceous chondrite anhydrous mineral (CCAM) line [1]. The systematics of the variation indicate that solar system solids are not derived entirely from a once chemically well-mixed reservoir but also from mixing of ^{16}O -rich and ^{17}O - ^{18}O -rich reservoirs during solid formation in the solar system. The ^{16}O -rich reservoir is a protoplanetary nebular gas based on the high temperature ^{16}O -rich condensates around Ca-Al-rich inclusions (CAIs) [2]. The most ^{16}O -rich end member has been reported from a chondrule, $\delta^{17,18}\text{O}_{SMOW} = \sim -80$ permil [3]. The ^{17}O - ^{18}O -rich reservoir is also a protoplanetary nebular gas based on the oxygen isotopic exchange feature in CAIs [4]. The most ^{17}O - ^{18}O -rich end member has been reported from new-PCP, $\delta^{17,18}\text{O}_{SMOW} = \sim +180$ permil [5]. The new-PCP indicates that the ^{17}O - ^{18}O -rich reservoir was related to primordial water in the solar system. The ^{17}O - ^{18}O -rich water has been inferred by self-shielding models of CO [6]. From these models, oxygen isotopic composition of the inner solar system changed from ^{16}O -rich to ^{17}O - ^{18}O -rich due to H_2O enrichment. The changing time scale is estimated to order of million years corresponding an age gap between ^{16}O -rich CAIs and ^{16}O -poor chondrules. The H_2O enrichment is consistent to higher oxygen fugacity of chondrule formation than of CAI formation.

References

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