COSMOCHEMISTRY

Meteorites have inherited nucleosynthetic anomalies of potassium-40 produced in supernovae

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Meteorites record processes that occurred before and during the formation of the Solar System in the form of nucleosynthetic anomalies: isotopic compositions that differ from the Solar System patterns. Nucleosynthetic anomalies are rarely seen in volatile elements such as potassium at bulk meteorite scale. We measured potassium isotope ratios in 32 meteorites and identified nucleosynthetic anomalies in the isotope potassium-40. The anomalies are larger and more variable in carbonaceous chondrite (CC) meteorites than in noncarbonaceous (NC) meteorites, indicating that CCs inherited more material produced in supernova nucleosynthesis. The potassium-40 anomaly of Earth is close to that of the NCs, implying that Earth's potassium was mostly delivered by NCs.

Nucleosynthetic anomalies are isotopic abundance patterns that deviate from the apparently uniform Solar System patterns. Their presence in primitive meteorites provides information about the production of nuclides in stars (stellar nucleosynthesis), the incorporation of elements into the Solar System during its formation, and the subsequent processing and transport of material in the solar nebula (the cloud of gas and dust from which the Solar System formed by condensation). Nucleosynthetic anomalies have been identified in bulk meteorites for several refractory elements, i.e., those that condense from the solar nebula before or concurrent with the major elements Mg, Si, and Fe (*1*), namely Ca (*2*), Ti (*3*), Cr (*4*), Fe (*5*), Ni (*6*), Mo (*7*), and Ru (*8*, *9*). However, despite sensitive searches (*10*), these anomalies are rarely seen in volatile elements, i.e., those that condense after the major elements.

The lack of detectable nucleosynthetic anomalies in volatile elements has been interpreted as indicating that extensive thermal processing in the hot solar nebula volatilized solid dust particles and homogenized the distribution of volatile elements in the Solar System, but not the refractory elements. For the moderately volatile element (MVE) potassium (K), variations of the $^{41}K/^{39}K$ ratios measured in bulk meteorites might reflect nucleosynthetic anomalies (*11*). However, the $^{41}K/^{39}K$ ratios correlate with $^{87}Rb/^{85}Rb$ ratios in carbonaceous meteorites, which could arise if K and Rb experienced mass-dependent isotope fractionation (processes that produce different isotope abundances in proportion to their masses) when they were evaporated and recondensed into chondrules (millimeter-sized glassy spherules) during meteorite formation (*12*). These competing interpretations cannot be distinguished with measurements of only two isotopes (^{41}K and ^{39}K), because the same ratio could arise from either mass-dependent fractionation or nucleosynthetic anomalies.

If the variations in the $^{41}K/^{39}K$ ratio are due to nucleosynthetic anomalies, then measurements of a third isotope (such as ^{40}K) will deviate from the mass-dependent relationship defined by the other two isotopes. However, ^{40}K has not been measured in meteorites because of its much lower natural abundance (the mole fraction of ^{40}K is 0.012% of total K atoms). Previous measurements of K isotopes (*11*, *12*) were limited by instrumental interferences from ^{40}Ar and ^{40}Ca, which are far more abundant than ^{40}K.

K isotope measurements

We sought to overcome this limitation using thermal ionization mass spectrometry (TIMS) to measure all three isotopes of K without interference from other elements. Meteorites are broadly divided into carbonaceous chondrite (CC) and noncarbonaceous (NC) families on the basis of their physical, chemical, and isotopic properties. We measured 32 bulk meteorites (table S1 and data S1A): 10 CCs (from the CI, CM, CV, CO, and CR subgroups), 18 NCs [enstatite chondrite (EC) groups EH and EL and ordinary chondrite (OC) groups H, L, and LL], and four martian meteorites. Because K is highly soluble in water, all but one of the samples that we selected were collected soon after observed falls to Earth to minimize any potential terrestrial contamination introduced by rain or dew. The K isotopic data are expressed using the $\varepsilon^{40}K$ notation as follows:

$$\varepsilon^{40}\mathrm{K} \equiv 10,000\left[\frac{\left(^{40}\mathrm{K}/^{39}\mathrm{K}\right)^{*}_{\mathrm{sample}}}{\left(^{40}\mathrm{K}/^{39}\mathrm{K}\right)^{*}_{\mathrm{terrestrial\ standard}}}-1\right] \quad (1)$$

where asterisks indicate that corrections have been applied to remove the mass-dependent fractionation component. The $\varepsilon^{40}K$ value would be zero for mass-dependent isotope fractionation and nonzero for isotopic anomalies.

Our measured $\varepsilon^{40}K$ variations in the bulk meteorite samples range from ~0 to +4.5, with typical uncertainties of ±0.4 (table S1). These variations are similar to the ranges of nucleosynthetic anomalies previously found for refractory elements (*2*–*9*).

Origins of the isotopic anomaly

These deviations of K isotopes from the terrestrial standards could have four causes: (i) inaccuracy of our correction for mass-dependent fractionation leading to an apparent anomaly; (ii) radioactive decay of short-lived ^{41}Ca to ^{41}K; (iii) excess ^{40}K through the reaction $^{40}Ca(n, p)\,^{40}K$ or spallation of Fe-group nuclides produced by cosmic ray exposure (CRE) of the meteorites during transfer to Earth (*13*); or (iv) pre–Solar System anomalies inherited from stellar nucleosynthesis.

To test scenario (i), we calculated corrections using several different mass dependencies in addition to the fiducial exponential function (*14*). We found a maximum apparent $\varepsilon^{40}K$ of ±0.06 (fig. S1), which is ~10 times smaller than the analytical uncertainty, so scenario (i) cannot be the cause of the observed variation. In scenario (ii), radioactive decay of ^{41}Ca would produce an excess in ^{41}K, and therefore a deficit in ^{40}K after correction for mass-dependent fractionation. This is inconsistent with our measurements of zero or positive $\varepsilon^{40}K$ values. In addition, the low initial $^{41}Ca/^{40}Ca$ ratio of the Solar System [~10^{-9} to 10^{-8} (*15*)] would produce only enough ^{41}K to contribute −0.02 to $\varepsilon^{40}K$ in bulk samples (*14*), which is 10 times smaller than our uncertainties and thus would not be detectable. For scenario (iii), we calculated the CRE-induced ^{40}K excess ($\varepsilon^{40}K_{CRE}$; see table S1 and fig. S2) using previously constrained ^{40}K production rates (*13*); the CRE age of each meteorite; and their K, Ca, and Fe concentrations (*14*). We found that $\varepsilon^{40}K_{CRE}$ is generally small in CCs, but larger in NCs because of their longer CRE ages. After deducting $\varepsilon^{40}K_{CRE}$ from the measured $\varepsilon^{40}K$, many meteorites still show ^{40}K excesses ($\varepsilon^{40}K_{Corr}$; see table S1 and fig. S3). To further determine whether the elevated $\varepsilon^{40}K_{Corr}$ values are due to nucleosynthetic anomalies, we focused on the samples with the lowest CRE corrections. About half of our samples have small differences between the measured $\varepsilon^{40}K$ and the values corrected for CRE (fig. S4). After this reduction in samples, most CCs show ^{40}K excesses (Fig. 1), whereas all but two NCs have $\varepsilon^{40}K_{Corr}$ values that are consistent with the terrestrial value. We infer that the observed ^{40}K excesses cannot be explained solely by CRE, and they must reflect pre–Solar System processes. We regard stellar

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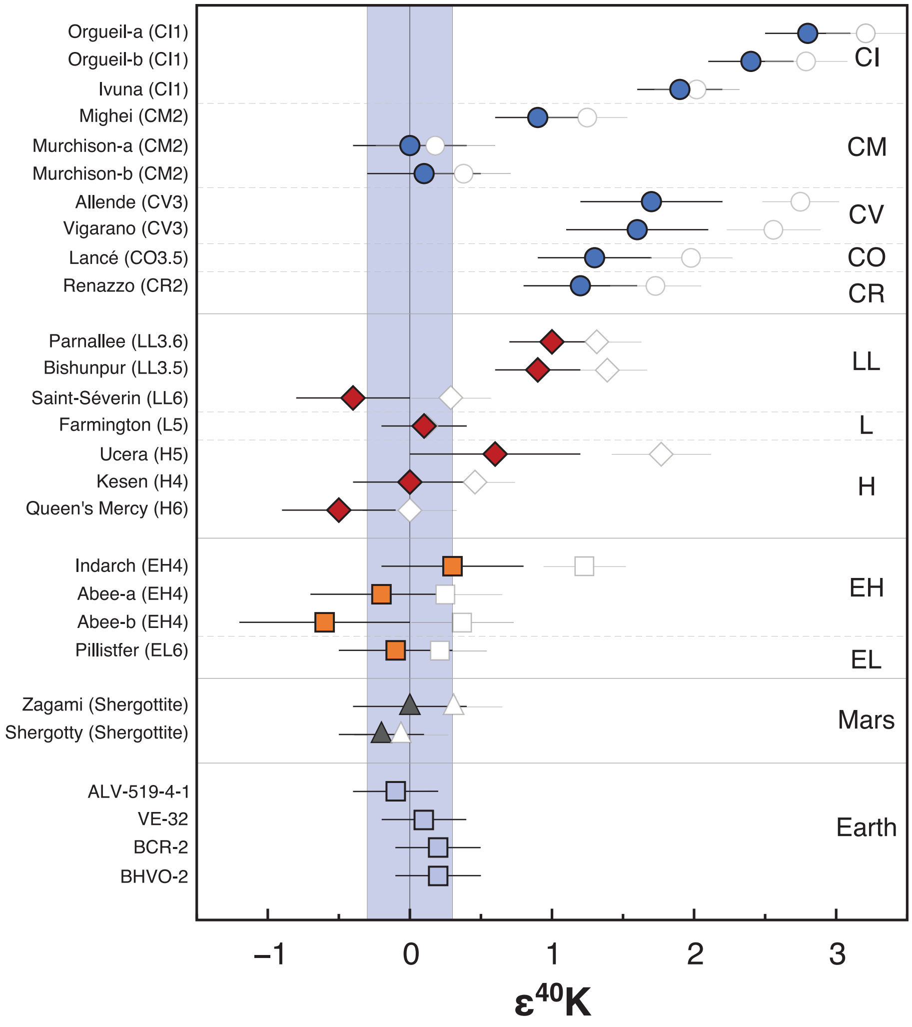

Fig. 1. K isotopic anomalies of meteorites with low CRE corrections. For each meteorite or terrestrial standard (labeled on the left), the empty and colored symbols represent K isotopic anomalies before and after CRE correction, respectively. Each color and symbol type indicates a class of meteorites (labeled on the right) that are separated by solid gray horizontal lines; dashed gray horizontal lines separate subclasses. The blue shaded region indicates the terrestrial range. Error bars indicate 95% confidence interval. Only samples with CRE corrections of $\varepsilon^{40}K \leq 1$ are shown here; fig. S3 shows all of the samples. The analytical uncertainty is ~±0.4 on this scale.

nucleosynthesis as the most likely cause of the K isotopic anomalies.

With only three isotopes, we cannot determine from the measurements alone which isotope is anomalous. Expressing the results as $\varepsilon^{40}K$ implicitly assumes that ^{40}K is anomalous, not the other two isotopes. However, a previous study (*11*) suggested that the variation of the $^{41}K/^{39}K$ ratio (without correction for mass-dependent fractionation) between meteorite groups indicates anomalies in ^{41}K. If this is correct, meaning that ^{41}K and not ^{40}K is the anomalous isotope, then the ^{41}K anomaly would have been reassigned to ^{40}K during our mass fractionation correction. In that case, our $\varepsilon^{40}K$ values would correlate with their $\delta^{41}K$ values

$$\delta^{41}K \equiv 1000\left[\frac{\left(^{41}K/^{39}K\right)_{\text{sample}}}{\left(^{41}K/^{39}K\right)_{\text{terrestrial standard}}} - 1\right] \quad (2)$$

with a slope of ~−5 (because $-\frac{10{,}000\left[M\left(^{40}K\right)-M\left(^{39}K\right)\right]}{1000\left[M\left(^{41}K\right)-M\left(^{39}K\right)\right]} \simeq -5$, where M is the mass of each isotope). However, we did not find such a correlation (Fig. 2A), indicating that the anomaly is in ^{40}K not ^{41}K. This is consistent with a previous suggestion (*12*) that the $\delta^{41}K$ variations among the CC groups reflect mass-dependent fractionation associated with chondrule formation and thus are not of nucleosynthetic origin.

Comparison with nucleosynthesis models

Models of stellar nucleosynthesis predict that ^{40}K is most likely the anomalous isotope. All three K isotopes are primarily produced during core-collapse explosions of massive stars (type II supernovae), but ^{40}K is produced by more nuclear reaction pathways than the other two isotopes (*16*, *17*). Using a set of existing supernova nucleosynthesis models (*18*), we tracked the production of K in a 25 solar mass ($M_\odot$) supernova (*14*). We assumed that the yield of this model is representative of the average from type II supernovae of all masses (*14*). The results show that ^{40}K is produced at different stages of the supernova than ^{39}K and ^{41}K (fig. S5). The production of ^{39}K and ^{41}K (including radiogenic ^{39}K and ^{41}K from short-lived ^{39}Ar and ^{41}Ca, respectively) occurs mainly in the O/Si/S zone of the supernova due to fusion of oxygen (O burning). By contrast, O burning accounts for <20% of ^{40}K production. Most ^{40}K is instead produced by C burning and the weak slow neutron capture process (weak s-process) in other zones (*14*). Individual zones of supernovae are usually homogeneously mixed because of convection, but different zones vary in composition (*18*). Therefore, the synthesis of ^{40}K is temporally and spatially decoupled from that of ^{39}K and ^{41}K, so ^{40}K is more likely to vary in abundance in different parts of the supernova ejecta.

Alternative nucleosynthesis origins could produce anomalies in ^{41}K due to radioactive decay of ^{41}Ca. This might occur in asymptotic giant branch (AGB) stars, where little K is synthesized, but ^{41}Ca could be produced through neutron capture by ^{40}Ca (*19*). Alternatively, cooling and condensation of supernova ejecta could fractionate Ca from K, because Ca condenses at a higher temperature than K (*16*). If condensation occurs before the decay of ^{41}Ca [half-life of 9.94×10^4 years (*20*)], then the first dust grains to condense would have high Ca/K ratios, leading to radiogenic ^{41}K

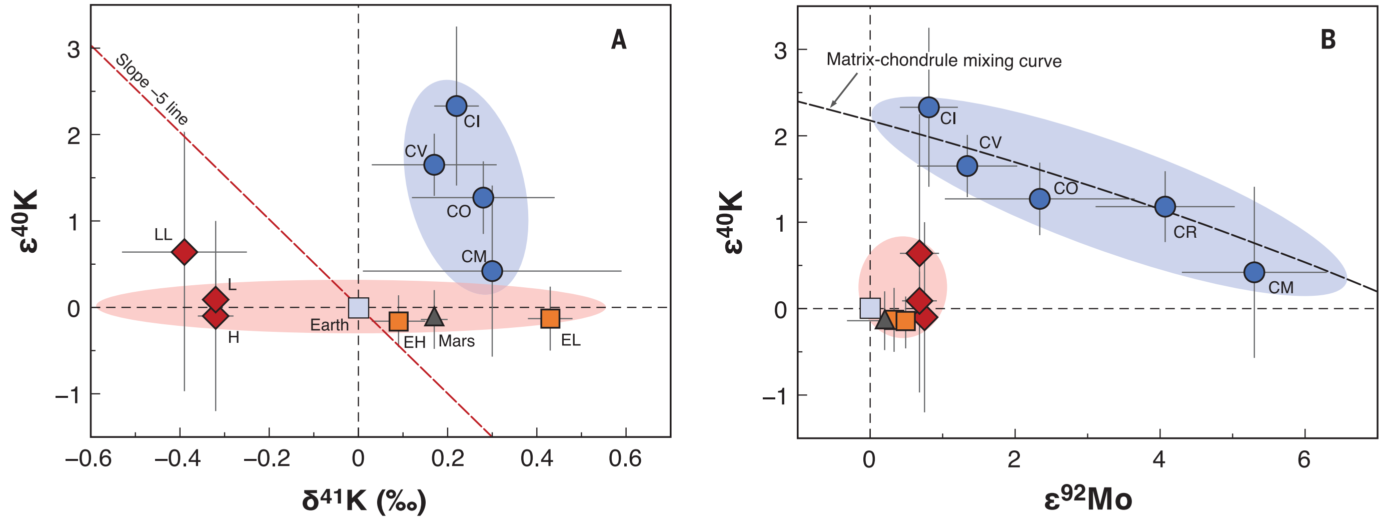

Fig. 2. Comparison of ^{40}K anomalies, δ^{41} values, and ^{92}Mo anomalies for different meteorite groups. Colored symbols represent different groups. Error bars indicate 95% confidence interval. Blue and pink areas represent CC and NC families, respectively. The horizontal and vertical dashed lines indicate the Earth values. (**A**) Average ε^{40}K for each meteorite class (after CRE correction; data S1D) shown as a function of δ^{41}K (*11*). The red dashed line indicates the slope −5 trend that would be expected if ^{41}K were anomalous and not ^{40}K. The data are not consistent with that interpretation. (**B**) Average ε^{40}K for each meteorite class as a function of ε^{92}Mo nucleosynthetic anomalies (data S1, D and E). The data are consistent with a CC-NC dichotomy. The dashed black curve shows a calculated matrix-chondrule mixing curve for CCs.

excesses once the ^{41}Ca decays. A complementary low Ca/K reservoir with ^{41}K depletion would be expected in the grains that condensed later, but the degree of ^{41}K depletion might be too small to be detectable. ^{41}K anomalies have only been detected as excesses in microscale presolar grains (*21*). Any excesses in ^{41}K would appear as deficits in ^{40}K in our measurements, as described above, so if any ^{41}K excesses are present, then our measured ε^{40}K values are lower limits.

We would expect large-scale ^{40}K heterogeneity in the interstellar medium. The abundance of ^{40}K decreases with time by decaying to ^{40}Ca and ^{40}Ar, with a half-life of 1.25 billion years (*22*). However, multiple generations of supernovae would inject freshly synthesized ^{40}K into their local interstellar medium, causing an enrichment of ^{40}K in those areas compared with the average interstellar medium. It is not known from which area the Solar System K is inherited, but if we assume that the difference between the ^{40}K enrichment in the supernova nucleosynthesis model and that in the Solar System reflects the decay of ^{40}K, then we can calculate an average delay of ~3 billion years between K production during supernova nucleosynthesis and the birth of the Solar System (*14*).

Dichotomy between CCs and NCs

Nucleosynthetic anomalies of refractory elements show distinct patterns for CCs and NCs (*23*, *24*). This CC-NC dichotomy has been attributed to barriers separating the inner Solar System (where NCs formed) from the outer Solar System (where CCs formed), combined with infall of additional material from the surrounding molecular cloud with a composition varying over time (*25*, *26*). The isotopic anomalies that we found for K are consistent with the CC-NC dichotomy previously defined by anomalies in refractory elements (Fig. 2B and fig. S6). The NCs in our sample have ε^{40}K values close to the terrestrial value, whereas the CCs show a wide range of excesses, suggesting that the CC reservoir received higher contributions of material produced in type II supernovae. However, there is no correlation between the anomalies of K and those of refractory elements, except for Mo in the CCs, which correlates with K [Fig. 2B and fig. S7 (*14*)]. The lack of correlation with most refractory nuclides is probably because these nuclides are produced by different nucleosynthetic processes [many of the relevant nuclides are primarily produced in type Ia supernovae, e.g., ^{48}Ca, ^{50}Ti, ^{54}Cr, and ^{64}Ni (*17*)] or because they condense onto different dust grains at different times than K because they are more refractory. In contrast to K isotopes, which are mainly synthesized in supernovae, bulk meteorites show Mo isotopic anomalies consistent with an s-process deficit, suggesting that Mo is predominantly produced in AGB stars (*27*–*29*). Therefore, the K and Mo anomalies are unlikely to have the same nucleosynthetic origin.

The correlation between K and Mo could reflect volatility control, because K is volatile and Mo becomes volatile under oxidizing conditions (*30*). The anomalies of refractory elements among the CC groups might reflect mixing between the three basic chondritic components (chondrules, refractory inclusions, and fine-grained matrix with similar composition to CI chondrites) in varying proportions (*31*). The abundance of refractory inclusions is related to the magnitude of the anomalies in bulk CCs for some refractory elements (e.g., Ca and Ti) but not for Mo (*31*). Mass balance considerations show that chondrules and matrix are the two dominant reservoirs for Mo (*29*) and K (*12*). We calculated matrix-chondrule mixing for K and Mo anomalies (*14*), finding that the CCs follow the theoretical mixing curves (Fig. 2B and fig. S7) between two end members: (i) matrix, with a large ^{40}K excess and ^{92}Mo deficit, and (ii) chondrules, with small or opposite anomalies. We expect the matrix to preserve the largest anomalies because it is less thermally processed than chondrules. The anomalies in matrix are consistent with nucleosynthesis in supernovae producing ^{40}K excesses and that in AGB stars producing ^{92}Mo deficits [figs. S5, S8, and S9 (*14*)]. Chondrules were formed by high-temperature heating of CI-like matrix (or dust with similar composition), which could have preferentially destroyed carriers of Mo and K anomalies, leading to smaller or opposite anomalies. Subsequent mixing between matrix and chondrules, in variable proportions, could have produced the K-Mo trend among CC groups (Fig. 2B). However, if this mixing model is correct, then the magnitudes of both K and Mo anomalies should increase with increasing mass fractions of matrix in the CC groups. We found that this is only true if the CM group is excluded (fig. S10). It is unclear why the CM group might be an outlier; possibilities include

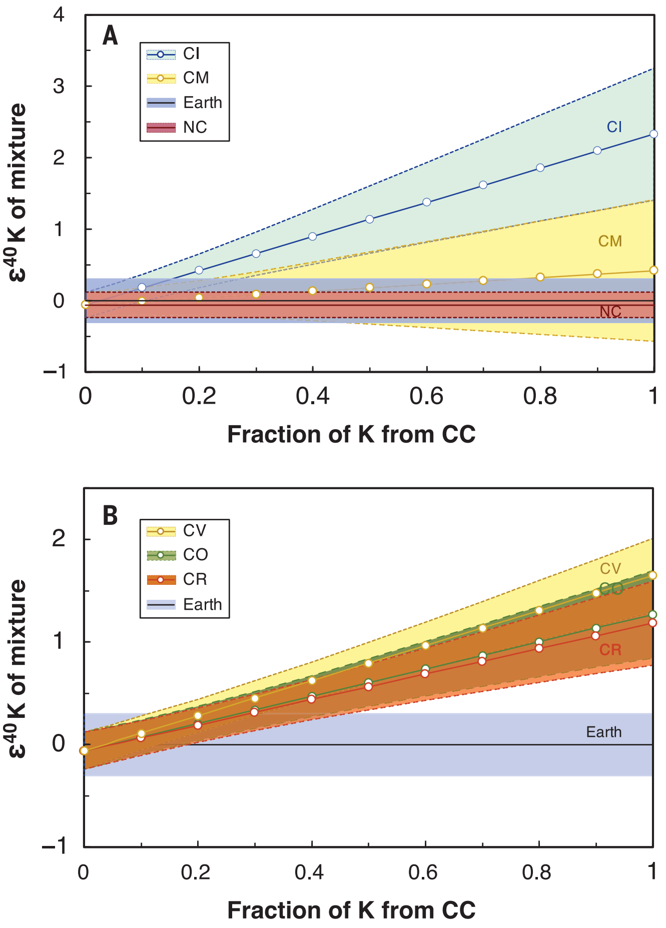

Fig. 3. Calculated fractions of Earth's K that could have originated from CC and NC reservoirs. The black line (with blue uncertainty region) shows Earth's ε^{40}K value of 0.0 ± 0.3, constrained by terrestrial standards. The results are split between two panels (A) and (B) with different vertical scales for clarity. For each CC meteorite group, we calculated the ε^{40}K that would result from a mixture between the NC reservoir (ε^{40}K = −0.06 ± 0.18, indicated by the red line and shaded uncertainty region) and different fractions of CC meteorites. Each CC group is represented by a solid line and a shaded uncertainty region in the same color (see legend); white dots denote the CC fraction from 0 to 1 in increments of 0.1. (**A**) Because the CM group has ε^{40}K = 0.42 ± 0.99, which overlaps with that of the Earth, any fraction of K from CMs is allowed. However, a large contribution (>20%) from CMs is inconsistent with other isotopic systems (*33*). If CI is the CC component, then the amount of K from CI is restricted to ≲10%. (**B**) For CV, CO, and CR chondrites, the K fraction is restricted to ≲20%. These calculations assume no volatile loss during Earth's accretion.

sampling bias or that CMs incorporated material from different reservoirs than other CC groups (*14*).

Origin of Earth's K

The implications of our ε^{40}K measurements for the sources of Earth's K and potentially other MVEs (*14*) are as follows. For unknown reasons, Earth is strongly depleted in MVEs compared with CI chondrites, which are thought to reflect the bulk Solar System composition. One possibility is that Earth initially accreted with a low abundance of volatile elements, then acquired them by later addition of CC-like materials (*32*). Another possibility is that volatile elements could have been delivered predominantly by NCs, which are thought to be the major building blocks of Earth (*33*). Our results show that Earth has an ε^{40}K value overlapping with those of NCs and CMs; however, CMs cannot be the dominant source of Earth's K because their K concentrations would require Earth to have an implausibly high fraction of CM material (~50% of Earth's mass), which contradicts constraints from several other isotopic systems (*33*).

We calculated the allowed fraction of Earth's K that could have been derived from CCs by assuming that it is from a mixture of NC and CC materials [Fig. 3 (*14*)]. We found that CCs contribute <20% of Earth's K, equivalent to a maximum contribution of ~13% to Earth by mass over all elements (assuming no volatile loss during or after delivery). This is consistent with previous estimates of several percent to 10% by mass (*33*, *34*), suggesting that Earth's K has a predominant NC origin. The small contribution of CCs for K and other elements (*33*, *34*) is incompatible with a pebble accretion origin of rocky planets (*5*, *35*), but is consistent with the hypothesis that dust-drift barriers separated the CC and NC reservoirs from each other (*25*, *26*, *34*).

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Competing interests: The authors declare no competing interests. **Data and materials availability:** All raw isotope measurements are provided in data S1, and the derived ε^{40}K values are listed in table S1. The sources of all meteorites and terrestrial standards are specified in the supplementary materials. The K and Mo nucleosynthesis calculations are available at Dryad (*36*).

SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S10
Table S1
References (*37*–*126*)
Data S1

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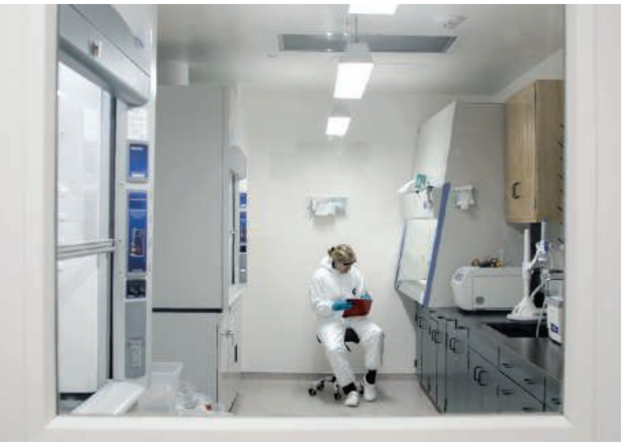
When the authors of the new study corrected for variables such as funding, time at SIO, and discipline that might explain the stark differences in space assignments, they came up empty. As faculty gained more funding, space assignments for men grew at four times the rate that women's did. And as the size of their research groups grew, men's research space expanded at nearly double the rate of women's. The gender gaps persisted across research disciplines, meaning the clustering of men in a field that needs more space—say, oceangoing research versus computational studies—could not explain the discrepancies. Nor did research space track with the length of time a scientist had been at the institution, making it unlikely that a longer average tenure for men could explain some of the disparities.

The task force also illuminated dramatic differences in perceptions between men and women among 77 active faculty who responded to an anonymous survey. Asked whether they had sufficient space for their work, 42% of women said no, versus 6% of men. Only 10% of women found space assignments to be transparent versus 28% of men.



Former Scripps Institution of Oceanography geologist Jane Willenbring, in her lab there in 2019, praises Scripps for publicizing its new findings.

One contributor to the lopsided space allocations is a practice called "inheritance," the authors write. SIO policy requires that space be returned to the institution for reallocation when a faculty member moves, dies, or retires, but the policy has at times been ignored when a departing principal investigator simply assigns their space to an heir—a practice that has disproportionately benefited men, especially those with the largest labs.

Also contributing are emeritus faculty, 86% of them men, who hold nearly one-quarter of all space at SIO. Their capacious assignments are "difficult to comprehend," write Stefanie Lutz, an environmental hydrologist at Utrecht University, and Andrea Popp, a hydrologist at the Swedish Meteorological and Hydrological Institute, in an email to *Science*. The pair were lead authors on a 2019 global survey on the impacts of gender discrimination in earth and space sciences.

The new report, which UCSD posted on its website, "is exceptional in how thoroughly it was done—but also because [the UCSD administration] publicized it afterward. They could have just put it into a hole," says Jane Willenbring, a geologist at Stanford University who was an associate professor at SIO from 2016 to 2020.

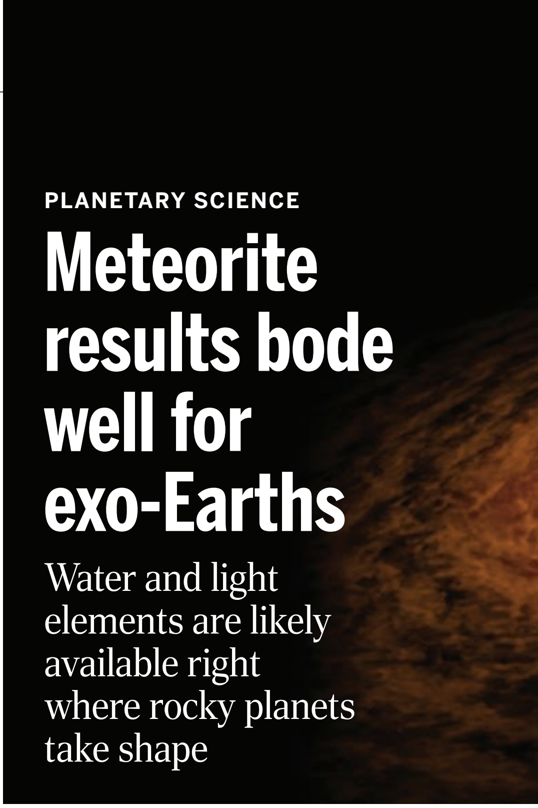
UCSD Chancellor Pradeep Khosla wrote in a cover letter: "These findings do not reflect the values of our university." Khosla said he had directed SIO Director Margaret Leinen, who has been in the job 10 years, to chair a "Change Management" committee implementing the report's many corrective recommendations. Those include immediately identifying and reassigning available and underused space and "addressing the space assignments" of retired faculty to better serve those who aren't retired.

"[It's] gonna get fixed," says Victor Ferreira, a psychologist who is UCSD's associate vice chancellor for faculty diversity, equity, and inclusion and headed the task force that authored the report. "Everything I have seen including the fact that the public can download this report suggests that the university doesn't want to whitewash this problem."

It will take concerted corrective action to convince the skeptical. "Nancy Hopkins did all of this work and shone this light on how different it can be to be a woman in science than to be a man in science. And we have just learned nothing from that," Willenbring says.

Other research institutions may soon receive similar wake-up calls. One woman, a junior geoscientist at a major university who asked not to be identified for fear of career repercussions, says that in 2020, with COVID-19 protocols dictating the precise amount of space required per person in the lab, "suddenly there were spreadsheets flying around … and blueprints of the department." She soon generated a color-coded bar graph showing men at all career levels ahead of women in lab space per capita. "It just jumped out at me and I was like, 'Holy crap, this isn't good.'"

"This is still an ongoing problem for everyone at every level," adds a woman faculty member at SIO who asked not to be named because of the sensitivity of the issues. "This is not just geoscience or Scripps. This is all of STEM [science, technology, engineering, and math]." ■



PLANETARY SCIENCE

Meteorite results bode well for exo-Earths

Water and light elements are likely available right where rocky planets take shape

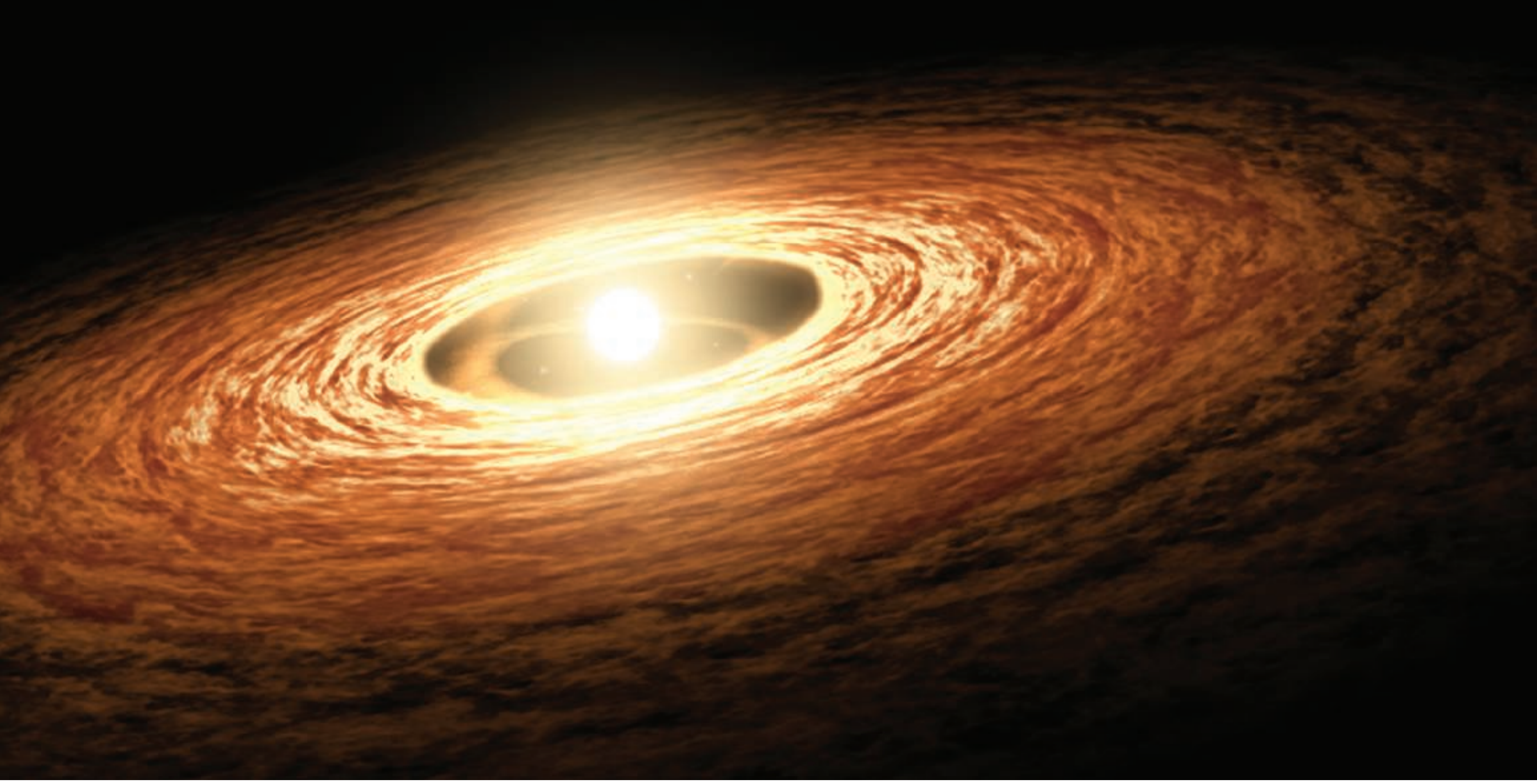
By **Paul Voosen**

How hard is it to give birth to an Earth? To assemble the right mix of rock, metal, and water, in a balmy spot not too far from a star? For a long time, planetary scientists have thought Earth was a lucky accident, enriched with water and lighter "volatile" elements—such as nitrogen and carbon—by asteroids that had strayed in from the outer edges of the early Solar System, where those materials were abundant. But a series of new studies, including two published today in *Science*, suggests all the ingredients were much closer at hand when Earth was born.

The findings, based on painstaking chemical analysis of meteorites, imply that planet-forming disks around other stars, too, should be well-stocked with the makings of wet, rocky planets that might be hospitable to life. "It makes the enrichment in volatile elements of a planet more generic," says Alessandro Morbidelli, a planetary scientist at the Côte d'Azur Observatory who wasn't part of the new work. Even if a young planet doesn't receive a delivery from the far reaches of the newborn planetary system, he says, "it doesn't change habitability."

Not that long ago, researchers thought the giant gas and dust disk that whirled around the early Sun more than 4 billion years ago had a fairly uniform composition. But that view was challenged by studies that tallied the ratios of certain isotopes found in the dozens of known species of meteorite. They indicated that the meteorites fell into two basic groups that likely originated in zones

IMAGES: (LEFT TO RIGHT) JANE WILLENBRING; NASA/JPL-CALTECH



A planet-forming disk around a young star (artist's concept) should readily give birth to habitable planets.

at different distances from the Sun. One group, known as carbonaceous chondrites, appears to have originated in the outer reaches of the early Solar System, beyond a proto-Jupiter and past the disk's "snowline," where temperatures cooled enough to allow water to freeze. In contrast, noncarbonaceous chondrites formed closer to the Sun. The isotopic signatures also suggested each zone was fed by material forged in different ancient and distant sources, such as supernovae and red giant stars (*Science*, 30 March 2018, p. 1451).

Until recently, scientists were only able to detect the early isotopic fingerprints in metals such as chromium, titanium, and molybdenum, which are durable enough to have resisted the heat of the newborn Sun. A close match between the isotope ratios found in noncarbonaceous chondrites and those found in the same metals on Earth suggested much of Earth's raw material came from the same nearby region as those meteorites.

But early searches for isotopic evidence that Earth's lighter volatile elements also originated nearby came up dry. "People just started thinking [the evidence] didn't exist," says Rayssa Martins, a doctoral student in geochemistry at Imperial College London (ICL). And so the traditional view of those elements' origin persisted: Many were assumed to come from a distant source, such as an outer region of the disk, where they might have condensed and then been pulled inward by the gravity of a forming planet, such as Jupiter.

Now, however, the meteorite divide has been detected in two moderately volatile elements, potassium and zinc. And the results suggest that much, but not all, of the planet's volatiles also came from the noncarbonaceous reservoir, says Nicole Nie, a planetary scientist at the California Institute of Technology and lead author of the potassium-focused paper. "This is a game changer for cosmochemistry."

The work was challenging, Nie says. Although a 2020 paper had identified what looked like ancient isotopic signatures in meteorite potassium, it only used two potassium isotopes, leaving out the much rarer potassium-40, whose signature in mass spectrometers is easy to confuse with those of calcium or argon. With only two isotopes, it was impossible to confirm that what the team saw reflected the chemical makeup of the primordial disk. And so Nie and her team measured all three potassium isotopes in 32 meteorites. They found that the potassium in the noncarbonaceous rocks showed isotopic patterns quite similar to those seen on Earth. "That was really surprising," she says. Together, the findings suggested some 80% of Earth's potassium came from nearby sources.

Three other teams have found a similar signal in the five stable isotopes of zinc. Two of the groups published their findings in *Icarus* last summer; work by the third, led by Martins, appears this week in *Science*. The findings complement each other, says Frédéric Moynier, a cosmochemist at the Paris Globe Institute of Physics and co-author of one *Icarus* study. "I agree with everything in the [*Science*] paper, because it's very similar to our paper." Overall, it appears that half or more of Earth's zinc also came from the inner Solar System.

Other volatile elements probably had a similar origin, says Mark Rehkämper, a geochemist at ICL. "Zinc is not water. But where you have zinc, you will have more water." And although the newly formed inner Solar System was low in volatile elements overall, there was still enough to create a habitable world. "The water has been here almost from the beginning," Moynier says.

The hunt will now be on for additional volatile elements that exhibit the primordial fingerprints, says Thorsten Kleine, director of the Max Planck Institute for Solar System Research and co-author of one of the zinc papers. "We have just written the proposals to do that, to be honest," he says. Armed with enough data, especially for elements that are known to accumulate in a newborn planet at different stages of its growth, "you can do a detailed reconstruction of how the material that built the Earth changed over time."

That could help resolve another question that has nagged at planetary scientists for decades: how quickly the rocky planets were built. They may have formed slowly, over tens of millions of years, as smaller rocky bodies collided with each other, or much more quickly, as vast clumps of material collapsed. The isotopes could hold clues—and not just for our Solar System. As the new work makes clear, the recipe for Earth is unlikely to be a one-off. ■