COSMOCHEMISTRY

Nucleosynthetic isotope anomalies of zinc in meteorites constrain the origin of Earth's volatiles

Rayssa Martins*†, Sven Kuthning†‡, Barry J. Coles, Katharina Kreissig, Mark Rehkämper*

Material inherited from different nucleosynthesis sources imparts distinct isotopic signatures to meteorites and terrestrial planets. These nucleosynthetic isotope anomalies have been used to constrain the origins of material that formed Earth. However, anomalies have only been identified for elements with high condensation temperatures, leaving the origin of Earth's volatile elements unconstrained. We determined the isotope composition of the moderately volatile element zinc in 18 bulk meteorites and identified nucleosynthetic zinc isotope anomalies. Using a mass-balance model, we find that carbonaceous bodies, which likely formed beyond the orbit of Jupiter, delivered about half of Earth's zinc inventory. Combined with previous constraints obtained from studies of other elements, these results indicate that ~10% of Earth's mass was provided by carbonaceous material.

The Solar System formed from an initially hot protoplanetary disk; as the disk cooled, refractory (high condensation temperature) metals and metal oxides were the first materials to condense into solid dust grains, followed by Fe metal and Mg silicates (*1*). The relative abundances of these refractory elements in all Solar System bodies are similar to those found in the Sun and in Ivuna-type carbonaceous chondrite (CI) meteorites, which are thought to be representative of the Solar System as a whole (*2*). Volatile elements (which have condensation temperatures below those of Mg, Si, and Fe) condensed later, and all other groups of meteorites are depleted in volatiles as compared to CIs, to various extents (*2–5*). This depletion was inherited by the terrestrial planets; it has been measured for Earth, the Moon, Mars, and Mercury (*6–9*). It is unclear how these bodies obtained their volatile elements.

The origins of Earth's building blocks can be constrained using nucleosynthetic isotope anomalies measured between bulk meteorites and the bulk silicate Earth (BSE). These small isotopic variations are produced by heterogeneous distribution of isotopically distinct material during the formation of the Solar System. This distinct material is inherited from presolar processes, such as nucleosynthesis in stars or supernovae. Known nucleosynthetic anomalies reveal an isotopic dichotomy between carbonaceous and noncarbonaceous (NC) meteorites (*10*). The carbonaceous group consists primarily of carbonaceous chondrite (CC) meteorites, and the NC group consists of enstatite chondrite (EC) and ordinary chondrite (OC) meteorites. In comparison to NCs, CCs have higher abundances of neutron-rich isotopes of the Fe-peak elements Ca, Ti, Cr, and Ni, and lower abundances of the slow neutron capture (s-process) nuclides of Zr, Mo, Ru, and Pd (*10–15*). It has been proposed that this dichotomy resulted from spatial separation of two isotopic reservoirs, with NC material in the inner Solar System, and CC material on orbits outside that of Jupiter (*16*).

The isotopic signature of the BSE indicates that Earth accreted primarily from NC material, with a small but non-negligible contribution of CC material (*10*, *12*, *17–19*). However, previously reported nucleosynthetic isotope anomalies were for refractory metals, which have nearly uniform elemental abundance ratios throughout the Solar System. By contrast, ratios of volatile to refractory elements are variable in generally volatile-rich CCs and volatile-poor OCs, and even more so in ECs, with the latter presenting both severe volatile depletions and high volatile abundances that could potentially account for much of Earth's volatile inventory (*20*, *21*). Searches for nucleosynthetic isotope anomalies in the volatile elements K, Zn, and Te have been inconclusive (*22–26*).

Zinc isotope measurements

We measured bulk samples of 18 meteorites (table S1): 7 CCs from four major groups [CI, CM (Mighei type), CV (Vigarano type), and CO (Ornans type)], and 11 NC meteorites, including 7 OCs, 2 ECs, and 2 iron meteorites classified as members of the IAB complex. Zinc isotope data were measured using a multiple-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) (*27*). Results are presented in $\varepsilon^{i}Zn$ notation (eq. S1), denoting the parts-per-10,000 deviations of the $^{i}Zn/^{67}Zn$ ratio from the London Zn standard, which defines $\varepsilon^{i}Zn = 0$ for the BSE (*27*). Unless otherwise stated, all uncertainties are quoted as ±2 SE (twice the standard error of the mean).

We find small but resolvable deviations from the BSE for all meteorites that we measured (Fig. 1, Table 1, and table S2). The CCs have an excess in $\varepsilon^{70}Zn$ (a neutron-rich isotope), a smaller excess for $\varepsilon^{68}Zn$, and a depletion in $\varepsilon^{64}Zn$. The NC meteorites have complementary patterns, with negative anomalies for $\varepsilon^{70}Zn$ and $\varepsilon^{68}Zn$, but positive deviations for $\varepsilon^{64}Zn$. We find similar results if other isotope ratios are used for internal normalization [e.g., $^{64}Zn/^{67}Zn$ (fig. S1)]. Our measurements of BSE standards show no substantial deviations from $\varepsilon^{i}Zn = 0$ (Fig. 1).

Previous research has suggested that anomalies of the neutron-rich isotopes of other Fe-peak elements derive from either Type Ia supernovae (SNIa, thermonuclear explosions of white dwarfs) or electron-capture core collapse supernovae (ECSNe, explosions of certain types of massive star) (*11*, *28–30*). We therefore calculated the Zn isotope anomalies that would be produced by adding various mixtures of SNIa and ECSNe Zn to Earth's Zn (*27*), to assess whether the observed Zn isotope

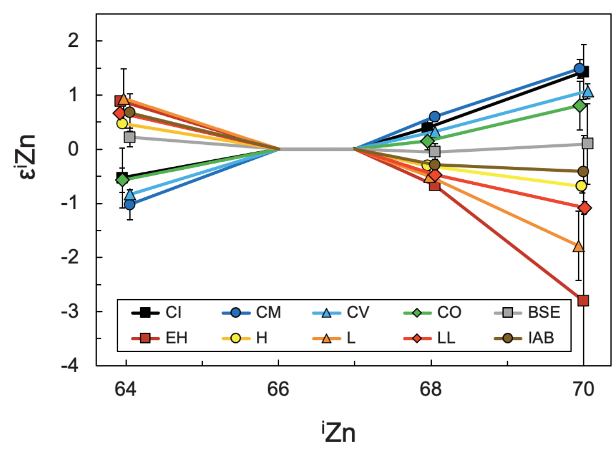

Fig. 1. Zinc isotope anomalies for each meteorite group and the BSE, in ^{i}Zn notation. Data are plotted for different groups of meteorites and the BSE (see the legend). Carbonaceous chondrites (CI, CM, CV, and CO chondrites) and noncarbonaceous-group meteorites [ECs, including two EHs (high iron); OCs, including H (high iron), L (low-iron), and LL (low-iron, low-metal) chondrites; and IAB complex irons] have complementary patterns with CCs enriched in ^{68}Zn and ^{70}Zn and depleted in ^{64}Zn relative to the BSE, which has $\varepsilon^{i}Zn = 0$. NCs have the opposite pattern, with depletions in ^{68}Zn and ^{70}Zn and enrichments in ^{64}Zn. There is no data for $\varepsilon^{66}Zn$ and $\varepsilon^{67}Zn$ because these isotopes are used for internal normalization. The meteorite and BSE data are listed in table S2; error bars indicate ±2 SE.

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Table 1. Mean, minimum, and maximum ε64Zn, ε68Zn, and ε70Zn values of the CC and NC meteorite groups. Results of all groups are listed in table S1. Uncertainties are ±2 SE (twice the standard error of the mean).

	ε^{64}Zn	2 SE	ε^{68}Zn	2 SE	ε^{70}Zn	2 SE
			CC			
Mean	−0.81	0.16	0.31	0.12	1.20	0.20
Min	−1.22	0.15	0.15	0.16	0.98	0.52
Max	−0.53	0.55	0.65	0.41	1.61	0.83
			NC			
Mean	0.75	0.18	−0.45	0.09	−1.39	0.62
Min	0.44	0.003	−0.70	0.16	−3.93	1.68
Max	1.61	0.61	−0.21	0.16	0.06	0.05

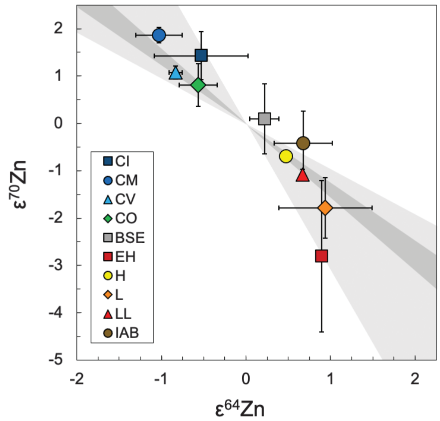

Fig. 2. ε^{70}Zn as a function of ε^{64}Zn for meteorite groups and the BSE. Data points indicate meteorite groups and BSE standards, using the same colors and symbols as Fig. 1. Shaded areas indicate predictions from models of Zn nucleosynthesis in Type Ia supernovae (*30*) in light gray, and electron capture supernovae (*28*) in dark gray (*27*). The meteorite and BSE data are listed in table S2; error bars indicate ±2 SE.

anomalies could have been generated by these nucleosynthetic sources. Plotting ε^{70}Zn as a function of ε^{64}Zn (Fig. 2) shows that the meteorite data have a negative correlation, which matches our models (*27*). We therefore conclude that the measured Zn isotope anomalies have a nucleosynthetic origin.

Dichotomy between CC and NC meteorites

Comparing ε^{70}Zn to anomalies in ^{48}Ca, ^{50}Ti, and ^{54}Cr (fig. S2) confirms the dichotomy in compositions between CC and NC meteorites. However, most of our meteorite data do not follow the isotopic trends predicted by combining nucleosynthetic production models of the different elements (fig. S2). It is nevertheless plausible for both the ε^{70}Zn enrichments and the ^{48}Ca, ^{50}Ti, and ^{54}Cr enrichments to be produced in the same nucleosynthesis sites, because the differing trends could be produced by the different physical and chemical properties of the elements. For example, moderately volatile Zn has a much lower 50% condensation temperature (T_{C50} = 726 K) than Ca, Ti, and Cr [T_{C50} ≈ 1290 to 1570 K (*31*)], so condensation of isotopically distinct Zn from SNIa and/or ECSNe into presolar dust grains was likely less efficient than for the more refractory elements (*15*, *32*). Zinc also has more affinity for sulfide than Ca, Ti, and Cr do (*33*), so isotopically anomalous Zn could have been concentrated into distinct mineral phases, which could have been lost during subsequent thermal processing during Solar System formation (*34*). Although the presolar carrier phases of the Zn anomalies are unknown, Zn in CCs is predominantly hosted in the fine-grained meteorite matrix, with Zn elemental abundances that exceed those found in chondrules (silicate spherules embedded in meteorites) by factors of 3 to 6 (*35*–*37*). Leaching studies have shown that Zn in chondrites is primarily (>80%) hosted in sulfides and silicates (*36*, *38*).

Nucleosynthetic isotope anomalies of more refractory metals display substantial isotopic diversity within the CC and NC reservoirs (*39*), but the Zn isotope data are much less variable. The mean Zn isotope compositions of all CC groups that we measured overlap within their uncertainties; we performed analysis of variance (ANOVA) tests and found that the groups are statistically indistinguishable (*27*). Likewise, the ε^{64}Zn values of the ECs, OCs and IABs all overlap within their uncertainties (Fig. 1 and table S2), with ANOVA tests indicating that these groups are also statistically indistinguishable (*27*).

Mass-balance calculations

The complementary Zn isotope anomalies of CCs and NC meteorites indicate a mixed source for Zn in the BSE. Because Zn did not partition strongly into metal during Earth's core formation (table S3), the nucleosynthetic Zn isotope composition of the BSE was built up throughout Earth's accretion history (*40*). We therefore assume that the BSE and bulk Earth (BE) have identical Zn isotope compositions. Chondrites are often assumed to be the building blocks of planets because they (mostly) preserve their original elemental and isotopic compositions and can account for most of the Solar System's isotopic diversity (*17*, *41*). We take the overall mean values of CCs (ε^{64}Zn = −0.81 ± 0.16, n = 7, where n is the number of meteorites) and ECs and OCs [noncarbonaceous chondrites (NCCs)] (ε^{64}Zn = 0.76 ± 0.22, n = 9) as representative of the CC and NC material accreted by Earth (table S2). We then calculate a mass balance to infer the contributions of each to Earth's Zn:

$$\varepsilon^{64}\mathrm{Zn}_{\mathrm{BE}} = x^{\mathrm{Zn}}_{\mathrm{CC}} \cdot \varepsilon^{64}\mathrm{Zn}_{\mathrm{CC}} + x^{\mathrm{Zn}}_{\mathrm{NCC}} \cdot \varepsilon^{64}\mathrm{Zn}_{\mathrm{NCC}} \quad (1)$$

where x^{Zn} is the Zn fraction derived from each reservoir, and $x^{\mathrm{Zn}}_{\mathrm{CC}} + x^{\mathrm{Zn}}_{\mathrm{NCC}} \equiv 1$. We performed a Monte Carlo simulation with 10,000 trials (*27*), in which the ε^{64}Zn compositions of the CC and NCC sources were allowed to vary within ±2 SE of their respective mean values, the fractions of Zn from each source ranged between 0 and 1, and the BE composition of $\varepsilon^{64}\mathrm{Zn}_{\mathrm{BE}}$ = 0 ± 0.17 was assigned an uncertainty corresponding to the long-term reproducibility of four BSE standards (table S2).

To reproduce the BE Zn isotope composition, we find that 48 ± 15% (uncertainty is 2 SD, twice the standard deviation) of Earth's Zn was derived from the CC reservoir, and the remainder from NCCs (fig. S3). In other words, CCs and NCCs contributed about equally to Earth's Zn. We obtain consistent (but more uncertain) results if other εZn values (e.g., ε^{70}Zn) or individual meteorite group means are used in the mass-balance equation (table S10). We adopt the results from ε^{64}Zn because its isotope anomalies are larger and more precise than those of other zinc isotopes.

We extended our mass-balance equation to constrain the mass fraction of carbonaceous material of all elements (x_{CC}) that was accreted by Earth:

$$\varepsilon^{64}\mathrm{Zn}_{\mathrm{BE}} = \frac{x_{\mathrm{CC}} \cdot [\mathrm{Zn}]_{\mathrm{CC}} \cdot \varepsilon^{64}\mathrm{Zn}_{\mathrm{CC}} + x_{\mathrm{NCC}} \cdot [\mathrm{Zn}]_{\mathrm{NCC}} \cdot \varepsilon^{64}\mathrm{Zn}_{\mathrm{NCC}}}{x_{\mathrm{CC}} \cdot [\mathrm{Zn}]_{\mathrm{CC}} + x_{\mathrm{NCC}} \cdot [\mathrm{Zn}]_{\mathrm{NCC}}} \quad (2)$$

and

$$[\mathrm{Zn}]_{\mathrm{BE}} = x_{\mathrm{CC}} \cdot [\mathrm{Zn}]_{\mathrm{CC}} + x_{\mathrm{NCC}} \cdot [\mathrm{Zn}]_{\mathrm{NCC}} \quad (3)$$

where x is the mass fraction of material from each reservoir, x_{CC} + $x_{NCC} \equiv$ 1, and [Zn] denotes Zn elemental abundances. We performed further Monte Carlo simulations of these equations using constraints on the Zn elemental abundance of the BE and CC material (*27*). Although the Zn elemental abundance of the BSE is well defined [54 ± 2 μg g^{-1} (table S3)], $[\mathrm{Zn}]_{\mathrm{BE}}$ is less well constrained at 40 to 70 μg g^{-1}, because the extent of Zn partitioning into

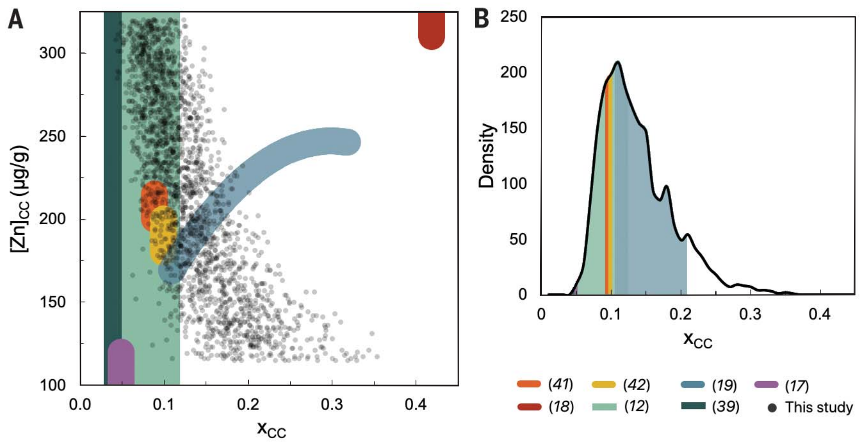

Fig. 3. Estimates for the mass fractions of accreted CC material (x_{CC}). (**A**) Zn elemental abundances plotted as a function of x_{CC}. Black dots show individual results from our Monte Carlo simulations, and colored regions indicate x_{CC} estimates from previous studies in orange (*41*), yellow (*42*), light blue (*19*), purple (*17*), red (*18*), light green (*12*), and dark green (*39*). (**B**) Probability density (black curve) of the estimated x_{CC} from our Monte Carlo simulations. Shaded regions indicate estimates from previous studies, using the same colors shown in (A). Our simulations have the highest density at $x_{CC} \approx 11\%$, equivalent to mean $[Zn]_{CC}$ concentrations of ~150 to 320 µg g^{-1}. Considering additional constraints from studies of other elements (*12*, *19*, *41*, *42*), the mean $[Zn]_{CC}$ elemental abundance is limited to ~170 to 220 µg g^{-1}, compatible with CM chondrites (table S3).

Earth's core is uncertain (table S3). For the CC material, the Zn elemental abundance was allowed to vary between 115 and 320 µg g^{-1}, because this variance encompasses the mean Zn abundances of CI, CM, and CO-CV chondrites (table S3). The Zn elemental abundances of ECs and OCs span a much wider range [7.5 to 519 µg g^{-1} (table S3)], so we treat $[Zn]_{NCC}$ as a free parameter. We find that 13 ± 10% (2 SD) of Earth's mass is derived from CC material (Fig. 3). At the lower end of this range (at $x_{CC} \approx$ 3 to 5%), Earth must have incorporated CI-like material; larger x_{CC} mass fractions require that increasing proportions of more volatile-depleted CCs were accreted (Fig. 3).

Comparison to other elements

We compare these results to previous studies that applied refractory-element and O isotope compositions to evaluate the origin of Earth's accreted material (Fig. 3). A CC mass fraction of 42% CI material has previously been proposed (*18*), based on differences in $\varepsilon^{48}Ca$ between the BSE and other inner Solar System bodies. For such a high CC fraction to be consistent with our Zn results, the BE Zn elemental abundance would need to be ~280 µg g^{-1} to produce $\varepsilon Zn_{BE} \approx 0$, far higher than the estimated BE Zn abundance [40 to 70 µg g^{-1} (table S3)]. Another study (*17*) inferred a much smaller CC contribution, of 5% CO-CV material, based on an inversion of refractory-element and O isotope compositions. In that case, the Zn contribution from the CO-CV component is too small to be compatible with the Zn isotope mass balance, requiring the BE to have only ~12 µg g^{-1} Zn, much lower than estimated (table S3).

Studies based on O isotope compositions have proposed that Earth accreted from a mix of ECs and OCs, with addition of 4% CI plus 5% CV material (*41*) or 10% CM-like material (*42*); these are consistent with our results for Zn. It has also been proposed (*19*) that Earth formed primarily from noncarbonaceous material composed of OCs and angrites (noncarbonaceous achondritic meteorites), with addition of 3 to 21% CI and 8 to 11% CV material. Although this estimate is consistent with our Zn isotope mass balance (Fig. 3), and we do not detect substantial variability within the NC reservoir, the lack of Zn isotope data for angrite meteorites prevents us from drawing firm conclusions about this scenario.

It is difficult to find a combination of meteoritic materials that can explain the BSE Mo isotope composition (*39*). It has been proposed that additional NC component, which was present in the early Solar System but is not represented in measured meteorites, is enriched in both s-process isotopes and neutron-rich nuclei of Fe-peak elements; if such a reservoir exists, it implies the accretion of ~4% CC material (*39*). This scenario can be reconciled with our Zn isotope data if Earth accreted CI-like material, but it conflicts with O isotope constraints (*41*, *42*). If the unidentified component is instead carbonaceous (*12*), the mass balance would allow for a larger CC contribution that is more consistent with our Zn isotope data. In the latter scenario, 30 to 60% of the BSE Mo budget would be derived from the carbonaceous reservoir (*12*). This can be reconciled with our Zn isotope constraints because Mo is more easily incorporated into Earth's core than Zn, so the BSE Mo isotope composition reflects only the final 10 to 20% of accretion, implying a minimum Mo-based x_{CC} of 3 to 12%. Therefore, a ~10% CC contribution composed of CMs or a mixture of CI, CM, and CO-CV chondrites can be reconciled with refractory-element nucleosynthetic isotope anomalies (*12*, *19*), O isotope constraints (*41*, *42*), and our Zn results (Fig. 3).

Origin of Earth's zinc

Our mass-balance calculations assume that the CC material and Earth did not experience Zn loss before or during accretion; the results then suggest that the NC material was, on average, depleted in Zn relative to CCs. Although some NC meteorites have high Zn elemental abundances [>300 µg g^{-1} (table S3)], an accretion scenario with a volatile-rich NC component and volatile-depleted CC material can only be accommodated in the Zn mass balance if x_{CC} is large. However, that is difficult to reconcile with refractory-element isotope compositions, which indicate a smaller contribution from CCs. Substantial loss of Zn from planets during their accretion, or directly from the accreting material, would introduce mass-dependent isotope fractionation. This would leave planets and meteorites enriched in heavy isotopes of volatile elements, as measured for Zn and K in lunar rocks (*43*, *44*). A similar signature is not observed for the BSE, indicating that Earth's volatile depletion arose from processes in the protoplanetary disk rather than from evaporation during subsequent accretion (*43*, *44*).

If the volatile elements in the BSE are representative of the accreting material, our results also constrain the mean Zn abundance of the NC material added to Earth. If about half of Earth's Zn, with $[Zn]_{BE}$ = 40 to 70 µg g^{-1}, was provided by NC bodies with a combined mass of 77 to 97% of Earth's, this implies a Zn abundance of 18 to 48 µg g^{-1} in the NC material. That is consistent with measured ranges for ECs (7.5 to 519 µg g^{-1}) and OCs [14 to 158 µg g^{-1} (table S3)]. Elements with condensation temperatures similar to Zn (500 K < T_{C50} < 750 K) are depleted by similar proportions in CCs, with an equivalent trend also observed for the BSE (*3*).

In conclusion, our Zn isotope data indicate that about half of Earth's Zn inventory was derived from carbonaceous material, which provided ~10% of the planet's mass. It is therefore likely that carbonaceous material also made substantial contributions to Earth's abundances of other moderately and highly volatile elements.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S10
Tables S1 to S11
References (*45–84*)
Data S1

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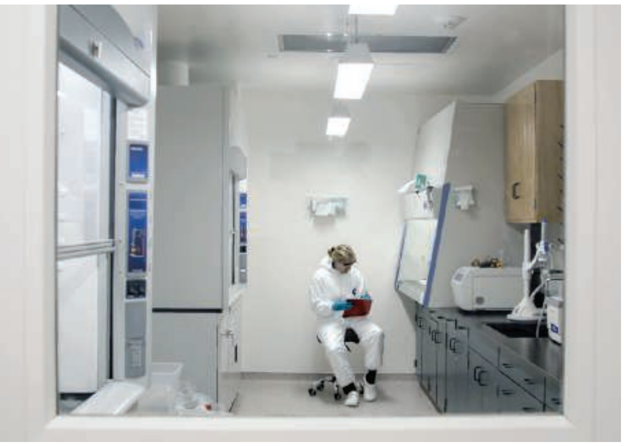
When the authors of the new study corrected for variables such as funding, time at SIO, and discipline that might explain the stark differences in space assignments, they came up empty. As faculty gained more funding, space assignments for men grew at four times the rate that women's did. And as the 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.

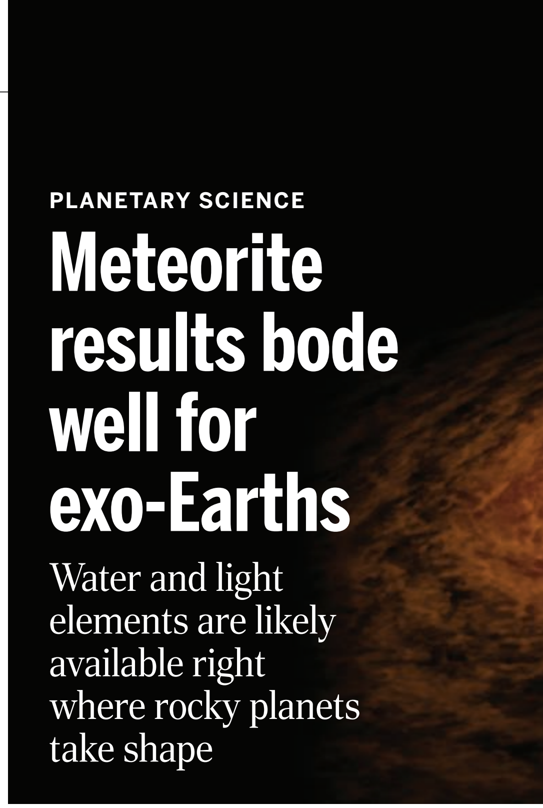
UCSD Chancellor Pradeep Khosla wrote in a cover letter: "These findings do not reflect the values of our university." Khosla said he had directed SIO Director Margaret Leinen, who has been in the job 10 years, to chair a "Change Management" committee implementing the report's many corrective recommendations. 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

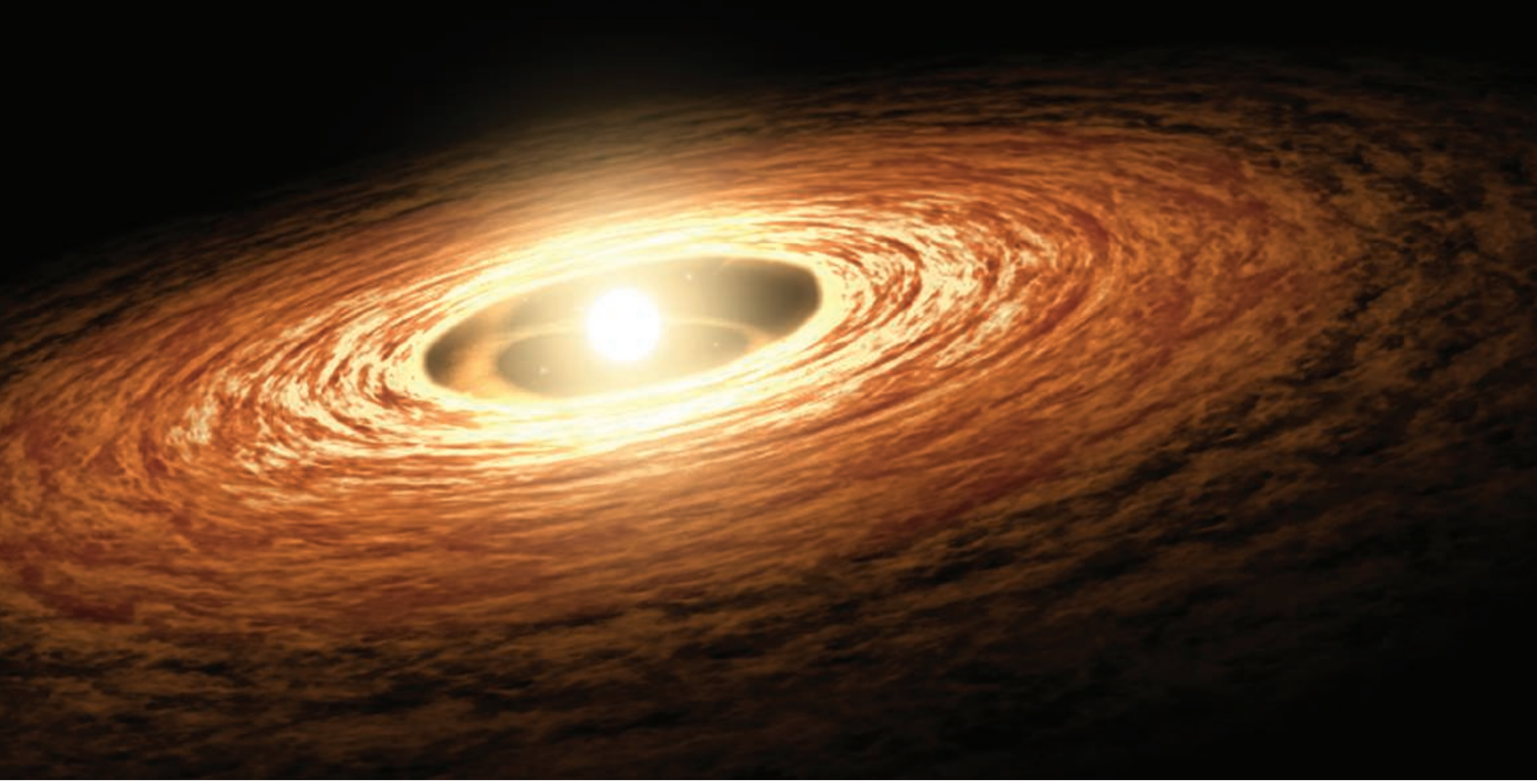
By **Paul Voosen**

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 coauthor 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. ■