The origin of s-process isotope heterogeneity in the solar protoplanetary disk

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Rocky asteroids and planets display nucleosynthetic isotope variations that are attributed to the heterogeneous distribution of stardust from different stellar sources in the solar protoplanetary disk. Here we report new high-precision palladium isotope data for six iron meteorite groups. The palladium data display smaller nucleosynthetic isotope variations than the more refractory neighbouring elements. Based on this observation, we present a model in which thermal destruction of interstellar dust in the inner Solar System results in an enrichment of s-process-dominated stardust in regions closer to the Sun. We propose that stardust is depleted in volatile elements due to incomplete condensation of these elements into dust around asymptotic giant branch stars. This led to the smaller nucleosynthetic variations for Pd reported here and the lack of such variations for more volatile elements. The smaller magnitude variations measured in heavier refractory elements suggest that material from high-metallicity asymptotic giant branch stars is the dominant source of stardust in the Solar System. These stars produce fewer heavy s-process elements (proton number $Z \geq 56$) compared with the bulk Solar System composition.

The protoplanetary disk from which our Solar System formed incorporated dust that was inherited from the collapsing molecular cloud. A few per cent of this dust formed around stars with active nucleosynthesis and retained the extreme isotopic fingerprint of its formation environment. This dust, which is isotopically anomalous compared with Solar System compositions, is here termed stardust. However, it is often also referred to as presolar grains when found in meteorites. Most stardust in primitive meteorites originates from asymptotic giant branch (AGB) stars, the site of s-process nucleosynthesis, with only small contributions from supernovae environments. The majority of the dust in the solar protoplanetary disk grew in the interstellar medium (ISM) from a well-mixed gas phase as mantles on pre-existing nuclei. These mantles probably inherited the composition of the local ISM—that is, a near solar isotopic composition.

Nucleosynthetic isotope variations, relative to Earth, are well established for a range of elements in bulk meteorites. These variations mostly reflect the heterogeneous distribution of isotopically distinct dust in the protoplanetary disk. It is generally thought that this heterogeneity began, at least in part, due to processes occurring in the protoplanetary disk itself. Physical sorting of grains, either by mineralogical type or size, and selective destruction of stardust by thermal processing in the protoplanetary disk or by aqueous alteration on parent bodies, have all been proposed as possible mechanisms to generate isotope heterogeneity. While these individual processes can explain nucleosynthetic variations for specific elements, it is debated whether a unifying explanation for all elemental trends exists. Therefore, considerable uncertainty remains as to which processes were important for dust processing in the protoplanetary disk.

Nucleosynthetic variations in bulk meteorites are mainly limited to refractory elements. The neighbouring refractory elements Zr, Mo and Ru display well-defined and linearly correlated nucleosynthetic variations. Each meteorite group shows a distinct s-process deficit in each of these elements, relative to Earth, which increases with the inferred formation distance of the meteorite parent body from the Sun. This can be accounted for by a heterogeneous distribution of isotopes of s-process origin in the Solar System. Moreover, no nucleosynthetic variations are reported for more volatile elements in the same mass region, for example, Cd (refs. 10,11) and Te (ref. 12), suggesting that the elemental condensation temperature plays a role in preserving nucleosynthetic variations. Palladium falls between Cd, Te and the refractory elements Zr, Mo and Ru in volatility, making it ideal for testing the link between volatility and the origin of the nucleosynthetic s-process variations. Earlier isotope data limited to the IVB iron meteorite group indicate that nucleosynthetic Pd offsets are smaller than predicted from Ru and Mo s-process deficits. Iron meteorites are enriched in siderophile elements such as Ru, Pd and Mo and show distinct nucleosynthetic variations for Mo (ref. 13) and Ru (ref. 14). They are thus ideal for constraining nucleosynthetic Pd isotope variations and their link to volatility.

Results

We determined Pd isotope compositions for 24 samples from the IAB, IIA, IID, IIBA, IVA and IVB groups (Supplementary Table 1; Methods). All data are presented in $\varepsilon$ notation, where $\varepsilon$ is the deviation of the sample isotope ratio from the terrestrial National Institute of Standards and Technology Standard Reference Material (NIST SRM) 3138 in parts per 10,000 (see Methods). Several iron meteorite groups show isotopic variations between their members, most notably the IIB and IVB irons (Extended Data Fig. 1). These variations are not related to nuclear field shift effects (Extended Data Fig. 2; Methods), but they correlate with Pt isotope ratios, which are affected by exposure to galactic cosmic rays and provide an established cosmic ray exposure dosimeter (Extended Data Fig. 3; Methods). After correction for cosmic ray irradiation, each group except the IAB irons exhibits a nucleosynthetic isotope composition distinct from the terrestrial standard (Fig. 1; Table 1). The negative $\varepsilon^{106}$Pd and $\varepsilon^{108}$Pd with concomitant positive $\varepsilon^{109}$Pd values indicate an s-process deficit in

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meteorites relative to Earth based on isotope yields of $s$-process models\textsuperscript{20} (Fig. 1). When plotting Mo, Ru and Pd isotope data together (Fig. 2), we find a linear relationship that traces the processes that generated the nucleosynthetic heterogeneities in planetary bodies.

**Mixing ISM-grown dust with stardust.** The linear correlation observed for samples from different bodies in our Solar System (Fig. 2) provides evidence for mixing between two isotopically distinct reservoirs, with at least one clearly distinct from the bulk Solar System composition. Here, we propose that these two reservoirs are stardust (isotopically anomalous) and ISM dust, whose isotopic composition closely resembles average Solar System composition. We argue that this stardust fraction mainly carries an $s$-process composition, because stardust with solar $p$- and $r$-process composition...
has not been unequivocally identified in meteorites. While some stardust grains show enrichments in p- and/or r-process isotopes, for example, SiC21,22 and nanodiamonds23,24, their composition does not mirror the r-process isotopic component of the Solar System. In addition, models of the weak r-process in core-collapse supernova neutrino winds do not predict isotopic abundances close to those of the Solar System r-process component20,33. Other models for the weak r-process, such as electron capture supernovae, favour the production of non-neutron-rich isotopes over classical r-process neutron-rich isotopes (for example 92Zr over 96Zr)26, but these signatures are not observed in stardust either. Furthermore, to mimic the s-process pattern identified in our data, stardust needs to contain the same proportion of p- and r-process material as the bulk Solar System. This is an unrealistic assumption given that the p-process is believed to occur in core-collapse supernovae, while the r-process is most likely to occur in neutron star mergers31,32, two distinct stellar environments. A small enrichment of supernovae derived material in the outer Solar System was proposed to account for the stellar environments. A small enrichment of supernovae derived stars reproduces the nucleosynthetic variations observed in Pd20,33. It is possible that different p- and r-process material are likely to represent only a minor fraction of the isotopically anomalous material that makes up stardust.

We therefore argue that the stardust reservoir, at first order, features an s-process composition and predominantly consists of material from AGB stars that became C-rich via recurrent mixing between the core and envelope (that is, a mass range of 1.5 to 4 M⊙, where M⊙ is the solar mass). These stars are the source of the vast majority of presolar SiC grains identified in meteorites. The solar s-process component estimated from the modelled yields of such stars27,28 reproduces the nucleosynthetic variations observed in Pd (Fig. 1) and Zr (ref. 9), Mo (refs. 11,14) and Ru (refs. 13,15) isotopes well. AGB stars with other masses remain O-rich and are instead the source of the vast majority of oxide and silicate stardust31,34. This dust does not contain observable s-process elements and is therefore unlikely to contribute a substantial fraction of elements heavier than Fe to stardust. Stardust contributions from the light-element primary process (LEPP) sources19 and spinstars28 are also unlikely, because they existed mainly in the early Universe. Given that the mean residence time for stardust in the ISM is a few hundred million years37, it is improbable that stardust from such environments survived until the formation of the Solar System. Any s-process nuclei produced in these environments are therefore part of the homogenized ISM dust fraction.

Table 1 | The nucleosynthetic Pd isotope composition of iron meteorite groups

| Group | ε^100Pd | ε^110Pd | ε^129Pd | ε^196Pd |
|-------|---------|---------|---------|---------|
| IAB   | 0.26 ± 0.26 | 0.01 ± 0.12 | –0.01 ± 0.02 | –0.05 ± 0.05 |
| IIAB  | 0.46 ± 0.60 | –0.12 ± 0.15 | –0.03 ± 0.07 | 0.05 ± 0.16 |
| IID   | 0.20 ± 0.38 | –0.56 ± 0.12 | –0.08 ± 0.06 | 0.32 ± 0.12 |
| IIIAB | –0.05 ± 0.97 | –0.29 ± 0.26 | –0.01 ± 0.09 | 0.22 ± 0.19 |
| IVA   | 0.11 ± 0.37 | –0.13 ± 0.07 | –0.02 ± 0.04 | 0.14 ± 0.09 |
| IVB   | –0.52 ± 0.41 | –0.66 ± 0.22 | –0.09 ± 0.06 | 0.39 ± 0.13 |

*Average of unexposed samples (Supplementary Table 2). Uncertainties represent two standard errors of the mean for all analyses from unexposed samples calculated using the homoscedastic method (see Methods). Calculated via regression against ε^106Pd (Supplementary Table 2). Uncertainties represent two standard deviations of the ε^106Pd intercept.

Incomplete condensation of elements around AGB stars. It is worth noting that the s-process deficits in Pd are smaller than predicted from the s-process depletion of Mo and Ru isotopes in the same meteorite groups (Fig. 2), in agreement with a previous study of IVB irons19. This implies that the relative abundance of Pd, compared with Zr, Mo and Ru, in stardust is 3–4 times lower than in the bulk s-process composition of the Solar System. Furthermore, Cd and Te concentrations must be even more depleted in stardust because of the absence of nucleosynthetic variations in these elements in bulk meteorites16,18. Changes in stellar parameters including initial mass and metallicity do not affect the relative yields of Zr, Mo, Ru, Pd and Cd (Fig. 4; Extended Data Fig. 5) and can therefore not explain the reduced abundance of Pd and Cd in stardust. Likewise, enhanced reaction rates of the 22Ne neutron source during AGB nucleosynthesis are unable to reduce the Pd yields relative to the neighbouring elements17. Therefore, the Pd depletion in stardust is not a consequence of stellar yields. We propose that it reflects incomplete condensation of elements into stardust around AGB stars as a function

Thermal processing of dust. In the context of our model (Fig. 3), the enrichment of s-process material in the inner Solar System was achieved through the destruction of ISM dust in this region by thermal processing such as photoevaporation induced by the radiation of the young Sun. Asteroids and planets forming in the inner region inherited this enrichment. Substantial processing of silicates could occur as material accretes onto the disk36 or during FU Orionis outbursts of the young Sun39. In line with this, previous studies proposed silicates as the likely phase being destroyed during thermal processing32,33. Another attractive mechanism is the removal of ISM-grown organic-rich icy mantles that are presumed to surround refractory dust grains40. Refractory elements can be implanted into such mantles by supernovae shockwaves in the ISM41. These volatile mantles will react to photoevaporation in the disk more rapidly than silicates and thus provide a wider temperature range in which thermal processing takes place, while preserving the refractory stardust. Such a mechanism was previously suggested to explain volatile depletion in the Solar System37. Evidence for thermal processing of primitive Solar System materials is provided by noble gases and the abundances of SiC, presolar diamond and insoluble organic matter in chondrites. Relative to CI chondrites, whose composition most closely matches that of the sun, many chondrite groups contain at least one dust component that has been processed at temperatures up to ~700 K (refs. 6,42). This may, at least partly, reflect thermal processing in the solar protoplanetary disk. Additionally, differences in the abundance of insoluble organic matter and crystalline silicates between ISM material, primitive Solar System material such as comets and interplanetary dust particles, and CI chondrites suggest that a substantial fraction of dust underwent thermal processing at temperatures of ~1,000 K or higher in the disk41. Later mixing between thermally processed and relatively pristine material can account for the abundances of presolar components with different thermal susceptibilities observed in meteorites38.

We estimated the amount of ISM dust that was removed to recreate the 0.02% s-process material excess in the Earth compared with carbonaceous chondrites43. About 0.37% of the initial dust mass was removed in the form of ISM dust, assuming that stardust has the same isotopic composition as the bulk Solar System s-process component, that stardust accounts for 3% of the dust mass in the Solar System42 and that the s-process accounts for 57.5% of the Solar System mass for elements heavier than Fe39 (see Methods for equations). This can be compared to the scenario where p- and r-process-enriched stardust is removed (analogous to equation (9) in Methods). This requires only 0.008% mass loss of the initial dust (~44 times less compared with removing ISM dust). However, as discussed above, we discard this latter option because it is improbable that different p- and r-process sources would produce dust with similar thermal properties and in the same proportion as the solar p- and r-process component.

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of the elemental condensation temperature (Fig. 3). Incomplete condensation refers to the scenario where only a fraction of the elements in the gas phase condense into dust, while the gas phase is lost. The typical temperature of dust forming regions around AGB stars is ~1,000 K (ref. 11), and hence a fraction of the elements with lower condensation temperature will probably be retained in the gas phase. Astronomical observations identified a distinct correlation between elemental abundances in the ISM gas phase and elemental condensation temperature45, indicating that more refractory elements are preferentially incorporated into dust. Evidence that the trace element composition of stardust depends on the elemental condensation temperature is provided by presolar SiC grains that have been shown to favourably incorporate refractory elements46–48. It has also been inferred that shock processing of dust in the ISM increases the concentration of volatile elements in the gas phase49. This suggests that dust enriched in more volatile elements is preferentially destroyed. Material that enters the ISM gas phase, either by direct transport from stellar environments or by the destruction of dust, is homogenized and anomalous isotopic signatures are lost. Therefore, incomplete condensation of elements around AGB stars and potential destruction of more labile stardust in the ISM can explain the smaller nucleosynthetic Pd variations relative to the more refractory Zr, Mo and Ru (Fig. 2) and the lack of nucleosynthetic variations in more volatile elements such as Cd and Te.

**Disconnect between light and heavy nuclides.** Nucleosynthetic deficits smaller than those in Zr, Mo and Ru are reported for a number of heavier elements, for example, Ba, Nd and W, while no variations are detected in Pt and Os (refs. 49,50). Many of these elements are highly refractory and therefore these observations cannot solely be explained by incomplete condensation around AGB stars. For example, the condensation temperatures of ZrC, MoC, HfC and WC at C/O ratios typical of low-mass AGB stars are all within the same range49. Instead, we propose that this trend was determined by the initial metallicity of the AGB stars that contributed the majority of stardust to the protoplanetary disk. The production of elements heavier than, and including, Ba ($Z \geq 56$; a magic neutron number) in AGB stars decreases as the metallicity increases, relative to Zr, Mo, Ru and Pd (Fig. 4). This is a well-known feature of the $^{13}$C neutron source in AGB stars41 (Extended Data Fig. 5), because Fe seeds are more abundant in higher metallicity stars and capture more neutrons, which reduces the production of heavier s-process elements. Meanwhile, the production of SiC and silicate dust increases as a function of metallicity52,53. Hence, most s-process stardust in the solar protoplanetary disk probably originated from AGB stars with high metallicities, which was also suggested to account for the isotopic composition of SiC grains48. Models predicting the contribution of silicate and SiC stardust from AGB stars with different metallicities to the Solar System also support this hypothesis55. As a result, the concentrations of heavier elements ($Z \geq 56$) in stardust, relative to Zr, Mo and Ru, are lower than in the bulk Solar System s-process component. The heavier elements are predominantly carried by ISM dust that incorporated homogenized material from AGB stars with a wide range of metallicities. This leads to the smaller or non-detectable nucleosynthetic offsets in the heavier ($Z \geq 56$) refractory elements.

**Origin of the non-carbonaceous–carbonaceous dichotomy.** An extension to our model can account for the isotopic dichotomy noted between carbonaceous and non-carbonaceous meteorites53, whereby carbonaceous groups are enriched in supernova-derived material. A small pervasive enrichment of supernova-derived material in the carbonaceous reservoir (Fig. 3) recreates the enrichment of light neutron-rich isotopes (for example, $^{56}$Ti or $^{54}$Cr) as
well as the negative shift in ε92Mo without changing the slope of the ε92Mo–ε100Mo correlation (Extended Data Fig. 4) in agreement with meteorite data\textsuperscript{11}. This can be attributed to a compositional change in the material infalling to the protoplanetary disk with time and/or by thermal processing\textsuperscript{30,31}, with complete homogenization between the two reservoirs (carbonaceous and non-carbonaceous) prohibited by the formation of Jupiter’s core\textsuperscript{55,56}. Therefore, a change in the composition of the infalling material is a viable addition to the model presented here (Fig. 3).

Conclusions

Our study represents a novel attempt to combine the nucleosynthetic variations identified in planetary bodies with data for presolar grains, results from astronomical observations on the origin and evolution of dust, and state-of-the-art nucleosynthetic models to explain the origin of planetary isotopic heterogeneity in our Solar System. We present a model that can simultaneously explain the origin of two prevalent nucleosynthetic features observed in rocky bodies: the subdued isotope variations in more volatile elements and heavier (Z ≥ 56) elements.

Methods

Samples. A total of 24 meteorites from the IAB, IIAB, IID, IIIAB, IV A and IVB iron meteorite classes were selected for Pd isotope analyses (Extended Data Fig. 1; Supplementary Table 1). Platinum isotope data were collected from the same sample aliquots and are published in refs. 50,59,60, except new Pt isotope data for the IVB iron meteorite classes were selected for Pd isotope analyses (Extended Data Fig. 1; Supplementary Table 1). A total of 24 meteorites from the IAB, IIAB, IID, IIIAB, IV A and IVB iron meteorite classes were selected for Pd isotope analyses (Extended Data Fig. 1; Supplementary Table 1). Platinum isotope data were collected from the same sample aliquots and are published in refs. 50,59,60, except new Pt isotope data for the IVB iron meteorites Tlacotepec and Hoba, the IV A iron meteorite Muonionalusta and the IID iron meteorite Rodeo (Supplementary Table 1). Four samples from the IID iron meteorite Carbo were analysed to evaluate the effects of cosmic ray exposure (CRE). These samples were taken from a cross section through Carbo and the CRE magnitude of each sample, inferred from offsets in ε92Mo without changing the slope of the ε92Mo–ε100Mo correlation (Extended Data Fig. 4) in agreement with meteorite data\textsuperscript{11}. This can be attributed to a compositional change in the material infalling to the protoplanetary disk with time and/or by thermal processing\textsuperscript{30,31}, with complete homogenization between the two reservoirs (carbonaceous and non-carbonaceous) prohibited by the formation of Jupiter’s core\textsuperscript{55,56}. Therefore, a change in the composition of the infalling material is a viable addition to the model presented here (Fig. 3).

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\[ ^{196}\text{Pt} \rightarrow ^{196}\text{Ptnormalized} = \frac{\text{e}^{196}\text{Pt}_{\text{sample}} \times \text{Rh/Pd}_{\text{sample}}}{\text{Rh/Pd}_{\text{median}}} \]
Nucleosynthetic variations are typically attributed to the removal of material in the solar nebula rather than the addition of material. To achieve this we rewrite equations (5) and (6) as:

\[ x_{\text{rockybody}} = x_0 + \frac{x_t + x_p}{1 + z} \]  
\[ x_{\text{rockybody}} = x_{\text{standard}} + \frac{x_{\text{ISM dust}}}{1 + y} \]  

Note that while the relative mass of the rocky bodies in equations (5) and (6) are identical, this is not true for equations (9) and (10). However, the relative proportion of the different nucleosynthetic components remains the same for the rocky body produced all four equations. Because \( x_{\text{rockybody}} \) is the same as \( x_{\text{rockybody}} \) when \( z = 0 \) or \( y = 0 \), we can calculate the mass fraction of dust that has been removed (\( f_{\text{dust}} \)) to create a planetary body with a given nucleosynthetic composition using the following equation:

\[ f_{\text{dust}} = 1 - \frac{x_{\text{rockybody}}}{x_{\text{solarbody}}} \]  

The largest uncertainty in these calculations is the assumption that the stardust material being removed/enriched has the same composition as the bulk \( x_t \) or \( x_p \) components. The composition of stardust is difficult to constrain as few data are available in literature. For example, if the abundance of trace elements in stardust/ISM dust is only half that of the bulk Solar System composition, then \( f_{\text{dust}} \) increases by a factor of two in both scenarios discussed in the main text. The presence of small amounts of \( p- \) and \( r- \) process stardust would also lower the magnitude of the overall \( s- \) process composition of stardust, again increasing the value of \( f_{\text{dust}} \).

Data availability

The authors declare that the original data supporting the findings of this study are available within the paper and its Supplementary Information. Original Pd and Pt data points for individual meteorites are also available from the EarthChem library (https://doi.org/10.1594/IEDA/111416). All other data are available from the corresponding author on reasonable request.

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Author contributions

M.S. designed the research project. M.E. prepared the samples for isotope analyses and conducted the measurements with assistance from A.C.H. M.E. did the data interpretation and wrote the first draft of the manuscript with important input from M.S., A.C.H. and M.I. All authors contributed equally to subsequent revisions of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Palladium isotope composition of iron meteorites from the IAB, IIAB, IID, IIIAB, IVA and IVB groups. All epsilon values are reported relative to $^{102}$Pd and internally normalised to $^{102}$Pd/$^{103}$Pd. Uncertainties on data points reflects the 2 standard error of the mean.
Extended Data Fig. 2 | Nuclear field shift effects on Pd isotopes. (a) The Pd isotope pattern produced by nuclear field shift effects, internally normalised to $^{108}\text{Pd}/^{105}\text{Pd}$ (short dashed line) and $^{108}\text{Pd}/^{106}\text{Pd}$ (solid line), calculated using the equations from Ref. 89 and the charge radii from Ref. 90. (b) $\varepsilon^{110}\text{Pd}$ against $\varepsilon^{105}\text{Pd}$ (internally normalised to $^{108}\text{Pd}/^{106}\text{Pd}$; Supplementary Table 1) for five individually processed aliquots of Toluca (IAB), Odessa (IAB), the other IAB meteorites, Rodeo (IID) and four aliquots of Carbo (IID) sampled at different locations within the meteorite. The solid line shows the nuclear field shift trend, internally normalised to $^{108}\text{Pd}/^{106}\text{Pd}$, and the dashed line shows an $s$-process deficit/excess trend calculated using the $s$-process yields of Ref. 20. Uncertainties are shown as the 2 standard error of the mean.
Extended Data Fig. 3 | Cosmic ray effects (CRE) on Pd isotopes in iron meteorites. Regressions of (a) $\varepsilon_{102}\text{Pd}$, (c) $\varepsilon_{104}\text{Pd}$, and (d) $\varepsilon_{106}\text{Pd}$ against $\varepsilon_{196}\text{Pt}$ for the IAB, IID and IVB groups. Panel (b) shows regressions of $\varepsilon_{104}\text{Pd}$ versus $\varepsilon_{196}\text{Pt}$ multiplied by the Rh/Pd ratio of the sample, to account for varied CRE contributions from $^{103}\text{Rh}(n,\beta)^{104}\text{Pd}$, for the same three groups. Individual samples and the slope of the regression are normalised to the intercept for each isotope/group such that the slopes can be compared directly. The black line shows the modelled CRE trend for each isotope, taken from Ref. 72. The slope of the regressions for $\varepsilon_{102}\text{Pd}$, $\varepsilon_{104}\text{Pd}$, $\varepsilon_{106}\text{Pd}$ and $\varepsilon_{110}\text{Pd}$ overlap for all three groups and agree well with the modelled slope. Uncertainties on individual data points given as the 2 standard error of the mean. Uncertainty envelope around regressions represents the 2 standard deviations of the regression calculated using the equation from Ref. 91.
Extended Data Fig. 4 | Isotopic dichotomy between carbonaceous (CC) and non-carbonaceous (NC) meteorites in $\varepsilon^{100}\text{Mo}$-$\varepsilon^{92}\text{Mo}$ and $\varepsilon^{102}\text{Pd}$-$\varepsilon^{102}\text{Pd}$. (a) The dichotomy reported in Mo is characterised by an enrichment in $\varepsilon^{92}\text{Mo}$ for the CC meteorites (blue) relative to the NC group (grey). A small addition of supernova derived material to the stardust and/or ISM dust fraction coupled with thermal processing of ISM dust mantles can explain this offset. (b) Only the IVB irons of the two analysed CC-type iron meteorite groups (IID and IVB) show the negative shift in $\varepsilon^{102}\text{Pd}$ predicted by the isotopic dichotomy. Given the typical uncertainty on $\varepsilon^{102}\text{Pd}$ for individual meteorites ($\pm 1\varepsilon$; Supplementary Table 1) due to the large Ru correction on $^{102}\text{Pd}$ (Ref. 62), it is barely possible to resolve the expected effect. The dashed lines indicate a mixing line between an $s$-process endmember$^{33}$ and the terrestrial composition. The blue dashed line represents a mixing line between an $s$-process endmember$^{33}$ and the terrestrial composition with a 0.008% enrichment in the residual $r$-process component, estimated based on the Mo data. Mo data from Ref. 11 and Pd data from Table 1. Uncertainties on Pd data points reflect either the 2 standard error of the mean or the 2 standard deviation of the x-axis intercept of a regression against $\varepsilon^{196}\text{Pt}$ (See Table 1). Uncertainties on Mo data points reflect either the 2 standard error of the mean (data from Ref. 11) or the 95% confidence interval (data from Ref. 14).
Extended Data Fig. 5 | Elemental ratios as a function of metallicity for FRUITY, Monash and NuGrid s-process models for AGB stars with an initial mass between 1.5 - 4 M☉. The relative proportion of light s-process elements (Y, Zr, Mo, Ru, Pd and Cd) vary little with different metallicities and are independent of the initial stellar mass and nucleosynthetic model. All models show a clear trend with the yield of heavy s-process elements (Ba, Ce, Nd, Hf, W, Pt, Os) decreasing, relative to the light s-process elements, as the metallicity increases. Shown in panel Ce/Y are the observational data for Ba stars in grey. These also indicate a decrease in the Ce/Y ratio as a function of increasing metallicity. FRUITY data correspond to the total yield for non-rotating stars with a metallicity of 0.006, 0.08, 0.010, 0.014 and 0.020 and mass of 1.5, 2.0, 2.5, 3.0 and 4.0 M☉. Monash data depict the yields of stars with a metallicity of 0.007, 0.014 and 0.030 and mass of 1.5, 2.5, 3.0, 3.5 and 4.0 M☉ computed with a mass extension of the mixing leading to the formation of the main neutron source ¹³C of 2 × 10⁻³ (M ≤ 3) and 1 × 10⁻³ (M > 3). NuGrid data represent the final surface composition for stars with a metallicity of 0.01 and 0.02 and mass of 2.0 and 3.0 M☉. Elemental ratios are shown in standard spectroscopic notation where [El/E₁] = log(E₁/El₁) - log(E₁/El₁)₀, where El₁ and E₁ are abundances by number.