Early differentiation of magmatic iron meteorite parent bodies from Mn–Cr chronometry

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Abstract

Magmatic iron meteorite groups such as IIAB, IIIAB and IVA, represent the largest sampling of extraterrestrial core material from the earliest accreted distinct planetary bodies in the solar system. Chromium isotope compositions of chromite/daubréelite from seven samples, translated into 53Cr/52Cr model ages, provide robust time information on planetary core formation. These ages are within ~1.5 Ma after formation of calcium-aluminium-rich inclusions (CAIs) and define the time of metal core formation in the respective parent bodies, assuming metal-silicate separation was an instantaneous event that induced strong chemical fractionation of Mn from the more siderophile Cr. The early core formation ages support accretion and differentiation of the magmatic iron meteorite parent bodies to have occurred prior to the chondrule formation interval. The calibration of Mn–Cr ages with established Hf–W ages of samples from the same magmatic iron meteorite groups constrains the initial ε53Cr of the solar system to ~0.3 ± 0.05, and thus lower than previously estimated.

Introduction

Members of the different magmatic iron meteorite groups are thought to sample the cores of distinct parent bodies that experienced large scale chemical fractionation, most notably metal–silicate separation. The absolute time of core formation provides a key time marker for the evolution of early formed planetesimals including accretion and cooling of the respective parent body. The most commonly used chronological system to date iron meteorites is the 182Hf–182W system (Kruijer et al., 2017 and references therein), constraining core formation in iron meteorite parent bodies over an interval of ~1 Myr and their accretion to ~0.1–0.3 Ma after the formation of Ca-Al-rich inclusions (4567.18 ± 0.50 Ma; Amelin et al., 2010). These early accretion ages pred ate or are contemporaneous with the chondrule formation interval (e.g., Connelly et al., 2012; Pape et al., 2019). However, correct interpretation of Hf–W data depends on the accurate knowledge of initial ε182W of the solar system and Hf/W ratios of the parent bodies which are well established but still needs to consider possible variations in Hf isotopes due to galactic cosmic radiation (GCR) (Kruijer et al., 2017). Another powerful tool to constrain the time and duration of early solar system processes, including accretion, differentiation, metamorphism and subsequent cooling could be the short lived 53Mn–53Cr chronometer (t1/2 = 3.7 ± 0.4 Ma; Honda and Imamura, 1971) (e.g., Shukolyukov and Lugmair, 2006; Trinquier et al., 2008; Göpel et al., 2015; Zhu et al., 2021). Chromite (FeCr2O₄) and daubréelite (FeCr2S₄) are the two main carrier phases of Cr in magmatic iron meteorites. Both minerals have low Mn/Cr ratios (≤0.01; Duan and Reglou, 2014) and thus preserve the Cr isotope composition of their growth environment at the time of isotopic closure, while the in-growth of radiogenic 53Cr from in situ decay of 53Mn is negligible (Anand et al., 2021). This makes them suitable for obtaining model ages by comparing their Cr isotopic composition with the Cr isotope evolution of the host reservoir. A particular advantage is that low Fe/Cr ratios in chromite and daubréelite (typically ~0.5) result in negligible contribution of 53Cr produced by GCR from Fe; hence no correction for spallogenic Cr is required (Trinquier et al., 2008; Liu et al., 2019) (Supplementary Information).

This study presents model ages for chromite and daubréelite from the largest magmatic iron meteorite group collections (IIAB, IIIAB and IVA) that constrain the earliest stages of planetesimal formation and differentiation. These Cr model ages define the timing of metal segregation during core formation. Chromium-rich phases formed in the metal inherit the Cr isotope composition of their low Mn/Cr host and thus constrain the time of last silicate–metal equilibration.

Methods

A chromite or daubréelite fraction from seven iron meteorites was analysed. After mineral digestion and chemical purification, Cr isotopes were measured on a Triton™ Plus TIMS at the University of Bern. Each sample was measured on multiple filaments to achieve high precision for 53Cr/52Cr ratio. Isotope compositions are reported as parts per 10,000 deviations (ε notation) from the mean.

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value of a terrestrial Cr standard measured along with the samples in each session. External precision (2 s.d.) for the terrestrial standard in a typical measurement session was ±0.1 for ε54Cr and ±0.2 for ε44Cr (Supplementary Information).

Model for ε53Cr evolution in chondritic reservoir. Model 53Cr/52Cr ages for early formed solar system bodies and their components can be determined on materials with high Cr/Mn and considering the following (i) homogeneous distribution of 53Mn in the solar system (e.g., Trinquier et al., 2008; Zhu et al., 2019), (ii) known abundances of 53Mn and 53Cr at the beginning of the solar system (i.e., solar system initial 53Cr) or any point in time thereafter, (iii) an estimate for the Mn/Cr in the relevant reservoir, and (iv) known decay constant of 53Mn. Based on these assumptions the evolution of the 53Cr/52Cr isotope composition of the chondritic reservoir through time can be expressed as:

\[
(53\text{Cr}/52\text{Cr})_t = (53\text{Cr}/52\text{Cr})_i + (k)(53\text{Mn}/53\text{Mn})_t \times (1 - e^{-kt})
\]

where the subscripts ‘i’ and ‘t’ refer to the present day and initial solar system values, respectively, and \( k \) denotes the 53Mn decay constant. The \( {\text{Mn}}_{52}\text{Cr} \) of the reservoir is denoted by \( k \) and \( t \) represents the time elapsed since the start of the solar system, which is equated with the time of formation of CAIs. Equation 1 describes the evolution of 53Cr/52Cr with time for the chondritic reservoir and can be used to derive model ages for a meteorite sample by measuring the Cr isotopic composition of its chromite/daubréelite fraction.

Results

The ε53Cr and ε54Cr of chromite/daubréelite fractions determined for all samples are listed in Table 1. No correlation is observed in ε53Cr vs. ε54Cr and ε53Cr vs. Fe/Cr that corroborates an insignificant spallogenic contribution (Supplementary Information). Model ages are calculated relative to the CAI formation age of 4567.18 ± 0.50 Ma (Amelin et al., 2011) assuming an OC chondritic 53Mn/52Cr ≈ 0.74 (Zhu et al., 2021), a solar system initial ε53Cr = −0.23 and a canonical 53Mn/55Mn = 6.28 × 10⁻⁶ (Trinquier et al., 2008) (Fig. 1).

Discussion

The inference of Mn–Cr model ages to date core formation events is based on the assumption that metal–silicate separation was instantaneous. It occurred when the chondritic parent bodies of magmatic iron meteorites were heated by accretion energy and the decay of short lived 54Al, and reached the liquidus temperature of iron–sulfur alloy (1325 °C to 1615 °C, depending on the sulfur content in the metal melt; Kaminski et al., 2020 and references therein). The metal–silicate separation induced a strong chemical fractionation of Mn from the more siderophile Cr (Mann et al., 2009). The measured low Mn/Cr (±0.01; Duan and Regelous, 2014) in iron meteorites corroborates the efficiency of this fractionation. Because of the low Mn/Cr of the metallic core, its Cr isotopic composition remained unchanged and reflects the composition at the time of metal–silicate differentiation. Therefore, the Cr isotopic composition of chromite/daubréelite that formed in the metallic core, no matter at what time after the metal segregation, reflects the time of Mn/Cr fractionation from a reservoir with CI chondritic 53Mn/52Cr and not the time of mineral formation nor its closure below a certain closure temperature.

The Mn–Cr model ages determined using Equation 1, assume a Mn/Cr for the source reservoir that is represented by the average Mn/Cr of OCs. Ordinary chondrites have a CI-like Mn/Cr (e.g., Wasson and Allemeyn, 1988; Zhu et al., 2021) and alongside the investigated magmatic iron meteorite groups, belong to the ‘non-carbonaceous’ reservoir (Kleine et al., 2020). The effect of different Mn/Cr of the iron meteorite parent bodies and the assumption of different initial ε53Cr is shown in Figure S-2. Model ages for IIB, IIBa and IVA groups are unaffected by the growth trajectory chosen, given current analytical resolution. Assuming a Mn/Cr similar to carbonaceous chondrites would change the model ages by a maximum of 1 Ma for the youngest sample. However, since all samples belong to the non-carbonaceous group, the average composition of OCs is most appropriate.

Since the Cr isotopic composition of the samples is unaffected by contributions from spallogenic Cr (Supplementary Information), the only major source of uncertainty in Mn–Cr model ages comes from the choice of initial ε53Cr and 53Mn/55Mn values. Figure S-3 shows Mn–Cr model ages for the studied samples determined using initial Mn–Cr isotopic compositions from multiple studies reporting resolvable variations in the solar system initial ε53Cr and 53Mn/55Mn values. Clearly, more high precision Cr isotopic data for samples dated with different chronometers are needed to further constrain the initial ε53Cr and 53Mn/55Mn. Model ages determined using initial ε53Cr and 53Mn/55Mn values from Göpel et al. (2015) and Shukolyukov and Lugmair (2006) predate the CAI formation.

Table 1 Mn/Cr, Fe/Cr and Cr isotopic compositions of chromite and daubréelite fractions from iron meteorites.

| Sample (Coll. Number) | Group/Fraction | Mn/Cr | Fe/Cr | ε53Cr | 2 s.e. | ε54Cr | 2 s.e. | Model Agea | Model Ageb | n |
|-----------------------|----------------|-------|-------|-------|--------|-------|--------|-------------|-------------|---|
| Agoudal (43830)       | IIB/Chromite   | 0.0053(4) | 0.37(1) | −0.210 | 0.023 | −0.784 | 0.060 | 0.27±0.13 | 1.33±0.63 | 12 |
| Sikkote Alin (43880)  | IIB/Chromite   | 0.0052(8) | 0.41(3) | −0.228 | 0.025 | −0.923 | 0.051 | 0.03±0.16 | 1.04±0.58 | 12 |
| NWA 11420 (43877)     | IIB/Chromite   | 0.0040(1) | 0.59(1) | −0.203 | 0.045 | −0.768 | 0.055 | 0.37±0.25 | 1.45±0.80 | 7  |
| Saint Aubin1          | IIB/Chromite   | 0.0096(2) | 0.57(1) | −0.368 | 0.029 | −0.779 | 0.061 | −0.47±0.32 | 0.44±0.20 | 10 |
| Cape York (33137)     | IIB/Chromite   | 0.0062(3) | 0.46(1) | −0.196 | 0.043 | −0.780 | 0.062 | 0.47±0.38 | 1.57±0.74 | 13 |
| Yanhuatian (50084)    | IIB/Chromite   | 0.0190(7) | 0.54(1) | −0.272 | 0.027 | −0.468 | 0.061 | −0.52±0.36 | 0.38±0.15 | 10 |
| Duchesne (50033)      | IVA/Chromite   | 0.0048(4) | 1.11(1) | −0.160 | 0.037 | −0.487 | 0.156 | 1.00±0.53 | 2.23±0.80 | 7  |
| IAG OKUM               | whole rock std. | 0.60(6) | 36.69(9) | +0.020 | 0.065 | +0.083 | 0.110 | 7  | 7  |
age, contradicting the standard solar system model in which CAIs are the earliest formed solid objects. The Mn–Cr model ages determined using initial ε53Cr and 53Mn/55Mn from Trinquier et al. (2008) mostly postdate CAI formation and thus appear generally more reliable.

The Mn–Cr model ages can also be compared with other chronometers that have been used to date meteorites and their components. 182Hf–182W, 207Pb–206Pb and 187Re–187Os are some of the common chronological systems providing constraints on different stages in the evolution of iron meteorite parent bodies (Goldstein et al., 2009 and references therein). However, when applied to iron meteorites all other chronological systems date cooling below their respective isotopic closure with the exception of the 182Hf–182W system, which has strong similarities to the 53Mn–53Cr system. It is also suitable for examining the timescales and mechanisms of metal segregation for iron meteorite parent bodies since Hf and W have different geochemical behaviours resulting in strong Hf/W fractionation during metal/silicate separation (i.e. core formation). However, in addition to the uncertainty on the initial ε182W of the solar system, ε182W data are also affected by secondary neutron capture effects on W isotopes induced during cosmic ray exposure (unlike Mn–Cr model ages reported here). Recently, Pt isotope data have been used to quantify the effects of neutron capture on W isotope compositions, making it possible to produce more reliable core formation ages (e.g., Kruijer et al., 2017). The Mn–Cr core formation age corresponding to the weighted mean ε39Cr of combined IIAB, IIIAB and IVA groups determined using solar system initial ε39Cr = −0.23 (Trinquier et al., 2008) is ~1 Myr older than the Hf–W core formation age corresponding to Pt corrected weighted mean ε182W of the same iron groups (Fig. 2, Table S-2) (Kruijer et al., 2017). However, the Hf–W and Mn–Cr systems show consistent crystallisation ages in angrites (internal isochrons established by minerals) that also belong to the ‘non-carbonaceous’ reservoir and originated from differentiated parent bodies (Zhu et al., 2019). The different chronometers are expected to agree because of the rapid cooling of angrites indicated by their basaltic texture. A better fit between Hf–W and Cr model ages can be obtained when the uncertainties on the model parameters for Mn–Cr model age determination are considered. Uncertainties on the 53Mn decay constant (Honda and Imamura, 1971) and solar system 53Mn/55Mn (Trinquier et al., 2008) result in only a minor shift in the model ages of generally <0.02 Myr which is insignificant. However, using a solar system initial ε39Cr = −0.30, which is within its reported uncertainty (ε39Cr = −0.23 ± 0.09; Trinquier et al., 2008), results in a perfect fit with the mean 182Hf–182W model ages for magmatic iron meteorite groups (Fig. 2). Consequently, ε39Cr = −0.30 is proposed as a better estimate for the solar system initial ε39Cr. To maintain a match between Hf–W and Mn–Cr model ages the uncertainty on the initial ε39Cr of the solar system is less than ±0.05.

Figure 3 presents a timeline depicting chromite/daubréelite model ages for IIAB, IIIAB and IVA iron meteorites and parent body metamorphism ages for type 3 and 6 ordinary chondrites as determined in Anand et al. (2021) using updated parameters for model age calculation. Combined with the existing thermal models (e.g., Qin et al., 2008), Hf–W core formation ages and calibrated Mn–Cr model ages constrain the accretion of the magmatic iron meteorite parent bodies to within less
than 1 Myr and no later than 1.5 Myr after CAI formation. This is in perfect agreement with numerical simulations that require early and efficient accretion of larger bodies within the protoplanetary disk (e.g., Johansen et al., 2007; Cuzzi et al., 2008). The small spread in the model ages of samples from the same meteorite group might reflect some core–mantle exchange during the solidification of the metal core. The range is similar to the range of individual Hf–W model ages within an iron-meteorite group (e.g., Kruijer et al., 2017).

One of the most important implications of Mn–Cr and Hf–W (e.g., Kruijer et al., 2017; Spitzer et al., 2021) core formation ages is that they bring the accretion and differentiation of the magmatic iron meteorite parent bodies in context with the chondrule formation interval recorded in chondrite samples (e.g., Connelly et al., 2012; Pape et al., 2019, 2021). 207Pb–206Pb chondrule formation ages (Connelly et al., 2012) suggest that the production of chondrules began as early as the CAI condensation; hence, contemporaneous with the accretion of the parent bodies of magmatic iron meteorites as suggested by Hf–W core formation ages and collaborated by Mn–Cr model ages in the present study. 26Al–26Mg ages for the formation of melt in individual chondrules, as summarised in Pape et al. (2019), suggest that chondrule formation in ordinary and most carbonaceous chondrites lasted from 1.8–3.0 Ma with a major phase around 2.0–2.3 Ma after CAI formation. This puts the chondrule formation interval after the accretion of the magmatic iron meteorite parent bodies. The latter implies that chondrule formation may not necessarily be an intermediate step on the way from dust to planets, but rather early planet formation may have been the cause for chondrule formation at least in extant chondrite samples. Thus, the early planetesimal formation (i.e. accretion of the iron meteorites parent bodies) was a local process and happened while other regions were still mostly in the stage of accreting dust particles and chondrule formation. We thank Dr. Ludovic Ferriere from NHM Vienna for providing chromite from Saint Aubin meteorite. Dr. Harry Becker and Smithsonian Institution are thanked for providing Allende powder sample. Patrick Neuhaus and Lorenz Gfeller from the Institute of Geography, University of Bern, are thanked for assistance with the ICP-MS analysis of the samples. We thank Dr. Maud Boyet for editorial handling and Dr. Ke Zhu and an anonymous reviewer for their constructive comments that helped to improve the manuscript.

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## Additional Information

**Supplementary Information** accompanies this letter at [https://www.geochemicalperspectivesletters.org/article2136](https://www.geochemicalperspectivesletters.org/article2136). © 2021 The Authors. This work is distributed under the Creative Commons Attribution-Non-Commercial No-Derivatives 4.0 License, which permits unrestricted distribution provided the original author and source are credited. The material may not be adapted (remixed, transformed or built upon) or used for commercial purposes without written permission from the author. Additional information is available at [https://www.geochemicalperspectivesletters.org/copyright-and-permissions](https://www.geochemicalperspectivesletters.org/copyright-and-permissions). Cite this letter as: Anand, A., Pape, J., Wille, M., Mezger, K., Hofmann, B. (2021) Early differentiation of magmatic iron meteorite parent bodies from Mn–Cr chronometry. *Geochem. Persp. Let.* 20, 6–10. [https://doi.org/10.7185/geochemlet.2136](https://doi.org/10.7185/geochemlet.2136)

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Supplementary Information

The Supplementary Information includes:

- 1. Samples and Analytical Methods
- 2. Precision and Accuracy of Cr Isotope Data
- 3. Correction for Spallogenic Cr
- 4. Summary of (%Mn/55Mn) and ε53Cr
- Tables S-1 to S-3
- Figures S-1 to S-3
- Supplementary Information References

1. Samples and Analytical Methods

Seven samples from IIAB, IIIAB and IVA iron meteorite groups were analysed in this study. Chromite from whole rock iron meteorites, Sikhote Alin, Agoudal & Cape York and daubréelite from samples NWA 11420, Yahnuitlan & Duchesne (all from the Natural History Museum Bern) were separated. Pre-isolated chromite grains from sample Saint Aubin were received from the Natural History Museum Vienna. Sample collection numbers are provided in Table 1. At the University of Bern, chromite grains were identified using an optical microscope and isolated in small whole-rock fragments. The fragments were hand crushed using a pre-cleaned agate mortar and treated in conc. aqua regia on a hot plate set to 90 °C for 48 h to completely dissolve the metal-sulphide dominated matrix, leaving behind residual chromite grains. To separate daubréelite, whole meteorite fragment or troilite (sulphide) nodules were treated with conc. aqua regia at room temperature for 12 h and the residue was further separated into a magnetic and non-magnetic fraction using a magnet. Daubréelite grains were isolated from the non-magnetic portion and confirmed with energy dispersive X-ray spectroscopy (EDS) on a ZEISS EVO50 SEM. Consecutively, individual grains were handpicked. Chromite and daubréelite grains weighing 1–3 mg from all the samples were transferred to a 7 mL Savillex® vial with 150–250 mg ammonium bifluoride (ABF, NH₄F·HF, Sigma-Aldrich®, Trace Metal grade) and completely digested following the protocol described in O’Hara et al. (2017). The sample and reagent mixture was thermalized in a convection oven set to 230 °C for 48 h. Upon cooling, the mixture was dried down twice, first after treatment with 2 mL conc. HNO₃ and then after treatment with 1 mL conc. HNO₃ and 2 mL MilliQ® water.

Before chemical separation, an aliquot from digested chromite/daubréelite fraction from each sample was diluted in 10 mL 0.5 M HNO₃ to target for a 10 ppb Cr solution. These aliquots were used to determine Cr, Mn, and Fe concentrations using a 7700x Agilent ICP-MS at the Institute of Geography, University of Bern. Uncertainties on
Mn/Cr and Fe/Cr ratios are reported as 2 s.e. of the replicate measurements \((n = 5)\) and remained <5% for all the samples.

The procedure for Cr purification was adopted from Schoenberg et al. (2016). It includes three steps of a combination of cation–anion exchange chromatography modified after Schoenberg and von Blanckenburg, (2005) (column 1), Trinquier et al. (2008a) and Yamakawa et al. (2009) (column 2 and 3). In brief, an aliquot containing 15 µg Cr from each sample was taken up in 1 mL 6 M HCl and loaded on the first 7.5 mL Spectrum® polypropylene column containing 2 mL anion resin (BioRad® AG 1X8 100–200 mesh size). The Cr eluate from the first column was dried down, redissolved in 400 µL 6 M HCl, equilibrated on a hotplate set to 130 °C for ~30 min one day before the chemical separation and stored at room temperature overnight. The next day, the sample was re-equilibrated on a hot plate at 130 °C for one hour, diluted with 2 mL MilliQ® water to obtain 2.4 mL 1 M HCl and loaded on the second column filled with 2 mL cation resin (BioRad® AG 50W-X8 200–400 mesh size). The second column separation step produced a solution with mostly Cr, but incompletely separated from Ti and V. The third column with 0.5 mL BioRad® AG 50W-X8 200–400 mesh was used in order to obtain a clean Cr separate, free of Ti and V. The elute from the second column was dried down on a hot plate (at 90 °C), taken up in 0.5 mL conc. HNO₃ and dried down again immediately to transform the samples into nitrate form. The residue was redissolved in 3 mL 0.4 M HNO₃ for 30 min on a hotplate at 80 °C and let react cold for 5 days for the production of chloro-aquo complexes. Afterwards, each sample was loaded on the third column. The matrix was eluted in 8 mL 0.5 M HF and 9.5 mL 1 M HCl, and Cr was collected in 8 mL 4 M HCl. Finally, the Cr separate was redissolved in 100 µL conc. HNO₃ and dried immediately at 130 °C on a hotplate. This step was repeated two times until the residual organics from the column chemistry was completely destroyed. Typical recovery of Cr was in excess of 80% for the whole column chemistry, determined by measurement of spiked sample solutions on an ICP-MS. Total chemistry blanks were below 10 ng, which are negligible compared to the µg range of Cr isolated and loaded on the filaments for each sample. The purified Cr was dissolved in a sufficient amount of 6 M HCl to yield a solution with a Cr concentration of ca. 1 µg/µL for loading on Re filaments for mass spectrometry. 1 µg/µL Cr was mixed with 1.4 µL 6 M HCl and loaded on the filament, minimizing the spread of the sample droplet. 0.7 µL Al (1000 ppm) and 0.7 µL H₃BO₃ (5000 ppm B) was then added to the top of this mixture. After drying the mixture at around 0.8 A, the filament was heated slowly to a dull red glow for less than one second.

The samples were analysed by Thermal Ionization Mass Spectrometer using a Thermo Scientific TRITON Plus instrument at the Institute of Geological Sciences, University of Bern. Aliquots of each sample were loaded on multiple filaments and measured at 52Cr signal intensity between 8 and 12 V (10⁻¹¹ Ω resistor). Intensities of 54Cr, 51V, 52Cr, 53Cr, 54Cr, 55Mn and 56Fe were measured on the Faraday cups L3, L2, L1, C, H1, H2 and H3, respectively (Trinquier et al., 2008a). Alignment of all Cr peaks (peak scan) was ensured before each measurement and peak centre was monitored on 53Cr in the centre cup. Isobaric interference of 54Fe on 54Cr was corrected by monitoring 56Fe. The isotopes 49Ti and 51V were measured to correct for isobaric interferences on 50Cr. However, the 49Ti and 51V intensities remained indistinguishable from background intensities for all samples, verifying successful separation of V and Ti from Cr during column chromatography. A typical run for a single filament consisted of 24 blocks with 20 cycles each (integration time = 8.389 s), obtained in static acquisition mode. Gain calibration was done once, at the beginning of every measurement day. Amplifiers were rotated and the baseline was measured after every block (baseline = 30 cycles, each of 1.05 s). The Cr standard reference material NIST SRM 979, was used as a terrestrial reference material. The 53Cr/52Cr and 54Cr/52Cr ratios were normalized to 52Cr/50Cr = 19.28323 (Shields et al., 1966) by applying the exponential mass fractionation law and are reported as εCr, where εCr = ([Cr/52Cr]sample / [Cr/52Cr]NIST SRM 979) − 1) × 10⁴ and i = 53 or 54.

2. Precision and Accuracy of Cr Isotope Data

The εCr \((i = 53 \text{ or } 54)\) reported for any one sample represent the mean of the replicate measurements \((n = 7–13, \text{ Tables 1, S-1)}\). The replicate measurements for each sample are used to determine the external precision reported as 2 s.e. \((\text{Tables 1, S-1)}\). The isotopic compositions of each sample are reported relative to the mean value of the standard reference material (NIST SRM 979) measured along with the samples in each measurement session (single
turret). The external precision (2 s.d.) for the standard reference material (NIST SRM 979) in each measurement session was ~0.1 for $^{53}\text{Cr}$ and ~0.2 for $^{54}\text{Cr}$.

To estimate the analytical accuracy of Cr isotopic data, we evaluated the consistency of results obtained on both terrestrial standards and meteorite samples and compared to the published results. The Cr isotope data ($^{53}\text{Cr} = 0.072 \pm 0.066$, $^{54}\text{Cr} = 0.881 \pm 0.120$) for Allende (CV) agrees with $^{53}\text{Cr} = 0.11 \pm 0.02$ and $^{54}\text{Cr} = 0.95 \pm 0.06$, reported in Zhu et al. (2021). Cr isotope data for terrestrial rock standard IAG OKUM is also in good agreement with the Cr isotope data for terrestrial samples compiled in Zhu et al. (2021). Whole rock samples for an ordinary chondrite (Dergaon, H5) and Acapulcoite (RF 529) measured along with the iron meteorite chromite/daubréelite fractions are in good agreement with the literature (Zhu et al., 2021). Additionally, $^{54}\text{Cr} = −0.779 \pm 0.061$ and $^{53}\text{Cr} = −0.268 \pm 0.029$ for Saint Aubin chromite reported in the present study is in perfect agreement with $^{54}\text{Cr} = −0.81 \pm 0.08$ and $^{53}\text{Cr} = −0.28 \pm 0.06$ reported in Trinquier et al. (2007, 2008b).

3. Correction for Spallogenic Cr

Spallation reactions induced by cosmic-ray exposure (CRE) can alter $^{53}\text{Cr}$/52Cr and $^{54}\text{Cr}$/52Cr ratios in solar system objects. This alteration depends on the following parameters: (1) duration and intensity of cosmic ray exposure, (2) Fe/Cr ratio, and (3) shielding condition for any given sample/component. A particular advantage of analysing chromite and daubréelite in iron meteorites is that due to low Fe/Cr ratios in these phases, spallogenic contributions of $^{53}\text{Cr}$ and $^{54}\text{Cr}$ produced by galactic cosmic radiation (GCR) from Fe are negligible and hence no correction for spallogenic Cr is required (Trinquier et al., 2008b; Liu et al., 2019). Less suitable for dating is the iron metal of iron meteorites, because of its very high Fe/Cr combined with the typically long irradiation time in space for iron meteorites, which leads to significant production of spallogenic $^{53}\text{Cr}$ and $^{54}\text{Cr}$ that is difficult to correct for and results in high uncertainties. For instance, a Fe/Cr ratio of 0.5 (Fig. S-1b), which is typical in chromite and daubréelite would result in $^{53}\text{Cr}$ and $^{54}\text{Cr}$ excesses of 0.002 and 0.005, respectively, even if the CRE age for the iron meteorite is as high as 800 Ma ($^{53}\text{Cr}$ and $^{54}\text{Cr}$ excesses determined using equation given in Table 2 in Trinquier et al., 2007, and a $^{53}\text{Cr}$ and $^{54}\text{Cr}$ production rate of 2.9 × 10$^{11}$ atoms/Ma in Fe targets from Birck and Allégre, 1985). This spallogenic $^{53}\text{Cr}$ and $^{54}\text{Cr}$ contribution is well within the analytical uncertainties of the Cr isotopic measurements reported here.

Liu et al. (2019) measured Cr isotopic composition of 16 iron meteorites belonging to different chemical groups and showed that the CRE can cause coupled excesses in $^{53}\text{Cr}$ and $^{54}\text{Cr}$ with a linear correlation line of $^{54}\text{Cr} = (3.90 \pm 0.03) \times ^{53}\text{Cr}$. This correlation is independent of the duration and intensity of cosmic ray exposure, Fe/Cr ratio and shielding condition for any given sample/component and hence provide an alternate way to test the need for spallogenic Cr correction. Figure S-1a shows an $^{54}\text{Cr}$ vs. $^{53}\text{Cr}$ plot for the chromite and daubréelite separates from the analysed iron meteorites. The $^{54}\text{Cr}$ and $^{53}\text{Cr}$ values show no correlation for the analysed chromite/daubréelite fractions and corroborates to the negligible spallogenic contribution in these components.

4. Summary of ($^{53}\text{Mn}$/55Mn)$_i$ and $^{53}\text{Cr}_i$

Table S-3 provides a compilation of solar system initial ($^{53}\text{Mn}$/55Mn), and $^{53}\text{Cr}_i$, reported by different methods/approaches in the literature. Shukolyukov and Lugmair (2006), Morynier et al. (2007) and Göpel et al. (2015) determined the solar system initial ($^{53}\text{Mn}$/55Mn), and $^{53}\text{Cr}_i$ by evaluating the Mn/Cr data for bulk rock carbonaceous chondrites (CC) on a $^{55}\text{Mn}$/52Cr vs. $^{53}\text{Cr}$ diagram. Shukolyukov and Lugmair (2006) reported that the correlation line yields a $^{53}\text{Mn}$/55Mn of 8.5 ± 1.5 × 10$^{-6}$ and initial $^{53}\text{Cr}_i = −0.21 \pm 0.09$ at the time of Mn/Cr fractionation. Göpel et al. (2015) obtained a ($^{53}\text{Mn}$/55Mn)$_i = 6.24 \times 10^{-6}$ and $^{53}\text{Cr}_i = −0.15 \pm 0.10$ from the bulk rock CC isochron. Based on this value and with respect to the age of the solar system, the authors determined solar system initial ($^{53}\text{Mn}$/55Mn)$_i = 6.8 \pm 0.66 \times 10^{-6}$ and corresponding initial $^{53}\text{Cr}_i = −0.177$ (see Fig. 8 in Göpel et al., 2015). It is important to note that $^{55}\text{Mn}$/52Cr vs. $^{53}\text{Cr}$/52Cr diagram for bulk rock CC is sensitive to the choice of samples that are included into the regression calculation (Göpel et al., 2015; Zhu et al., 2021). Trinquier et al. (2008b) constrained ($^{53}\text{Mn}$/55Mn)$_i = 6.28 \pm 0.66 \times 10^{-6}$ using an isochron based on $^{54}\text{Cr}$-poor fractions of CI Orgueil and reported it as the best estimate for the solar system initial $^{53}\text{Mn}$ abundance. However, Zhu et al. (2021) reported that the $^{53}\text{Mn}$–$^{53}\text{Cr}$ correlation could be a
mixing line since chondritic components, e.g., CAIs, chondrules, matrix, metal, and carbonates have different origins and time of formation. To obtain the solar system initial $\varepsilon^{53}\text{Cr}$, Trinquier et al. (2008b) back-calculated $\varepsilon^{53}\text{Cr}$ for a wide range of chondritic reservoirs using present-day $^{53}\text{Cr}$$^{52}\text{Cr}$ and Mn/Cr ratios to the time of CAI formation and reported the average of all $\varepsilon^{53}\text{Cr}$ as solar system initial $\varepsilon^{53}\text{Cr} = -0.23 \pm 0.09$. Nyquist et al. (2009) used a correlation regression between initial ($^{53}\text{Mn}/^{55}\text{Mn}$), and initial ($^{26}\text{Al}/^{27}\text{Al}$) for solar system materials that have been analysed by both Mn–Cr and Al–Mg chronometers to determine the value of initial ($^{53}\text{Mn}/^{55}\text{Mn})_{\text{SS}} = (9.1 \pm 1.7) \times 10^{-6}$ corresponding to the assumed ($^{26}\text{Al}/^{27}\text{Al})_{\text{SS}} = 5.1 \times 10^{-5}$. In the present study, the solar system initial $\varepsilon^{53}\text{Cr} = -0.30 \pm 0.05$ is proposed after calibrating the Mn–Cr model ages for the core formation in magmatic iron meteorite to the corresponding Hf–W core formation ages. The proposed value agrees with the previously reported solar system initial $\varepsilon^{53}\text{Cr}$ values. Additionally, it also agrees with solar system initial $\varepsilon^{53}\text{Cr} = -0.34$ when ($^{53}\text{Mn}/^{55}\text{Mn})_{\text{SS}} = 3.16 \pm 0.11 \times 10^{-6}$ and $\varepsilon^{53}\text{Cr} = -0.10 \pm 0.06$ (Zhu et al., 2019) determined for bulk rock angrites are calibrated against the age of the solar system.

**Supplementary Tables**

Table S-1  $\varepsilon^{53}\text{Cr}$ and $\varepsilon^{54}\text{Cr}$ compositions of studied samples.

|   | $\varepsilon^{53}\text{Cr}$ | s.e. int. | $\varepsilon^{54}\text{Cr}$ | s.e. int. | mean | 2 s.d. ext. | 2 s.e. ext. | mean | 2 s.d. ext. | 2 s.e. ext. |
|---|-----------------|--------|-----------------|--------|-------|------------|------------|-------|------------|------------|
| IIA B |                 |        |                 |        |       |            |            |       |            |            |
| Agoudal (Chr) |                  |        |                 |        |       |            |            |       |            |            |
| AG_36_1           | -0.289 | 0.027 | -0.895 | 0.055 | -0.210 | 0.081 | 0.023 (12) | -0.784 | 0.206 | 0.060 (12) |
| AG_36_1b          | -0.161 | 0.024 | -0.875 | 0.051 |        |        |            |        |       |            |
| AG_36_1c          | -0.197 | 0.027 | -0.761 | 0.054 |        |        |            |        |       |            |
| AG_36_1d          | -0.235 | 0.027 | -0.947 | 0.056 |        |        |            |        |       |            |
| AG_36_1e          | -0.251 | 0.028 | -0.849 | 0.057 |        |        |            |        |       |            |
| AG_36_3           | -0.181 | 0.027 | -0.752 | 0.058 |        |        |            |        |       |            |
| AG_36_3b          | -0.182 | 0.029 | -0.789 | 0.059 |        |        |            |        |       |            |
| AG_36_4           | -0.187 | 0.031 | -0.707 | 0.063 |        |        |            |        |       |            |
| AG_36_5           | -0.257 | 0.036 | -0.693 | 0.074 |        |        |            |        |       |            |
| AG_53_1           | -0.234 | 0.032 | -0.805 | 0.069 |        |        |            |        |       |            |
| AG_53_2           | -0.151 | 0.032 | -0.792 | 0.062 |        |        |            |        |       |            |
| AG_53_3           | -0.193 | 0.029 | -0.539 | 0.065 |        |        |            |        |       |            |
| Sikhote-Alin (Chr) |                |        |                 |        |       |            |            |       |            |            |
| SA_36_1           | -0.159 | 0.028 | -0.821 | 0.053 | -0.228 | 0.087 | 0.025 (12) | -0.923 | 0.177 | 0.051 (12) |
| SA_36_2           | -0.255 | 0.030 | -1.014 | 0.062 |        |        |            |        |       |            |
| SA_36_3           | -0.249 | 0.026 | -0.931 | 0.057 |        |        |            |        |       |            |
| SA_36_4           | -0.189 | 0.025 | -1.036 | 0.059 |        |        |            |        |       |            |
| SA_36_4b          | -0.178 | 0.026 | -0.972 | 0.049 |        |        |            |        |       |            |
| SA_36_5           | -0.237 | 0.025 | -0.842 | 0.052 |        |        |            |        |       |            |
| SA_36_5b          | -0.253 | 0.024 | -0.966 | 0.050 |        |        |            |        |       |            |
| SA_53_1           | -0.188 | 0.029 | -0.846 | 0.060 |        |        |            |        |       |            |
| SA_53_1b          | -0.212 | 0.025 | -0.813 | 0.052 |        |        |            |        |       |            |
| SA_53_2           | -0.231 | 0.029 | -1.050 | 0.057 |        |        |            |        |       |            |
| SA_53_3           | -0.325 | 0.046 | -0.803 | 0.078 |        |        |            |        |       |            |
| SA_53_3b          | -0.256 | 0.030 | -0.978 | 0.062 |        |        |            |        |       |            |
Table S-1 continued

| Location     | Sample | $\epsilon^{53}$Cr | s.e. int. | $\epsilon^{54}$Cr | s.e. int. | $\epsilon^{53}$Cr mean | 2 s.d. ext. | 2 s.e. ext. ($n$) | $\epsilon^{54}$Cr mean | 2 s.d. ext. | 2 s.e. ext. ($n$) |
|--------------|--------|--------------------|-----------|--------------------|-----------|-------------------------|-------------|------------------|-------------------------|-------------|------------------|
| NWA 11420    | Daub_37_2 | −0.161             | 0.029     | −0.808             | 0.063     | −0.203                  | 0.118       | 0.045 (7)        | −0.768                  | 0.147       | 0.055 (7)        |
|              | Daub_37_3 | −0.183             | 0.031     | −0.731             | 0.064     |                        |             |                  |                         |             |                  |
|              | Daub_37_4 | −0.131             | 0.026     | −0.654             | 0.048     |                        |             |                  |                         |             |                  |
|              | Daub_53_1 | −0.161             | 0.029     | −0.680             | 0.067     |                        |             |                  |                         |             |                  |
|              | Daub_53_2 | −0.222             | 0.024     | −0.836             | 0.048     |                        |             |                  |                         |             |                  |
|              | Daub_53_3 | −0.320             | 0.032     | −0.854             | 0.069     |                        |             |                  |                         |             |                  |
|              | Daub_53_3b| −0.240             | 0.040     | −0.810             | 0.077     |                        |             |                  |                         |             |                  |
| IIIIAB       | CY_41_1  | −0.164             | 0.030     | −0.672             | 0.062     | −0.196                  | 0.154       | 0.043 (13)       | −0.780                  | 0.223       | 0.062 (13)       |
|              | CY_41_2  | −0.188             | 0.034     | −0.888             | 0.067     |                        |             |                  |                         |             |                  |
|              | CY_41_3  | −0.109             | 0.034     | −0.588             | 0.072     |                        |             |                  |                         |             |                  |
|              | CY_41_3b | −0.042             | 0.029     | −0.692             | 0.059     |                        |             |                  |                         |             |                  |
|              | CY_41_2b | −0.099             | 0.032     | −0.859             | 0.057     |                        |             |                  |                         |             |                  |
|              | CY_41_1b | −0.182             | 0.030     | −0.870             | 0.058     |                        |             |                  |                         |             |                  |
|              | CY_40_1  | −0.176             | 0.024     | −0.635             | 0.046     |                        |             |                  |                         |             |                  |
|              | CY_54_1  | −0.240             | 0.045     | −0.956             | 0.089     |                        |             |                  |                         |             |                  |
|              | CY_54_2  | −0.293             | 0.046     | −0.766             | 0.082     |                        |             |                  |                         |             |                  |
|              | CY_54_3  | −0.236             | 0.030     | −0.789             | 0.060     |                        |             |                  |                         |             |                  |
|              | CY_54_1b | −0.227             | 0.039     | −0.802             | 0.067     |                        |             |                  |                         |             |                  |
|              | CY_54_2b | −0.272             | 0.033     | −0.700             | 0.066     |                        |             |                  |                         |             |                  |
|              | CY_54_3b | −0.318             | 0.048     | −0.923             | 0.084     |                        |             |                  |                         |             |                  |
| Saint Aubin | S’Aub_50_1| −0.273             | 0.033     | −0.810             | 0.073     | −0.268                  | 0.091       | 0.029 (10)       | −0.779                  | 0.193       | 0.061 (10)       |
|              | S’Aub_50_3| −0.242             | 0.039     | −0.710             | 0.083     |                        |             |                  |                         |             |                  |
|              | S’Aub_50_2| −0.330             | 0.031     | −0.634             | 0.063     |                        |             |                  |                         |             |                  |
|              | S’Aub_54_1| −0.249             | 0.032     | −0.903             | 0.068     |                        |             |                  |                         |             |                  |
|              | S’Aub_54_1b| −0.256            | 0.031     | −0.880             | 0.068     |                        |             |                  |                         |             |                  |
|              | S’Aub_54_2| −0.326             | 0.033     | −0.926             | 0.070     |                        |             |                  |                         |             |                  |
|              | S’Aub_54_2b| −0.221            | 0.033     | −0.763             | 0.069     |                        |             |                  |                         |             |                  |
|              | S’Aub_54_3| −0.193             | 0.028     | −0.669             | 0.061     |                        |             |                  |                         |             |                  |
|              | S’Aub_54_3b| −0.333            | 0.028     | −0.803             | 0.061     |                        |             |                  |                         |             |                  |
|              | S’Aub_54_3c| −0.255            | 0.029     | −0.696             | 0.061     |                        |             |                  |                         |             |                  |
| IVA          | Yan_55_1 | −0.192             | 0.030     | −0.351             | 0.057     | −0.272                  | 0.085       | 0.027 (10)       | −0.468                  | 0.193       | 0.061 (10)       |
|              | Yan_55_1b| −0.273             | 0.027     | −0.587             | 0.056     |                        |             |                  |                         |             |                  |
|              | Yan_55_2b| −0.254             | 0.032     | −0.529             | 0.065     |                        |             |                  |                         |             |                  |
|              | Yan_55_2b| −0.285             | 0.032     | −0.397             | 0.067     |                        |             |                  |                         |             |                  |
|              | Yan_55_2c| −0.335             | 0.027     | −0.583             | 0.061     |                        |             |                  |                         |             |                  |
|              | Yan_55_2d| −0.234             | 0.029     | −0.502             | 0.063     |                        |             |                  |                         |             |                  |
|              | Yan_55_3 | −0.228             | 0.029     | −0.269             | 0.058     |                        |             |                  |                         |             |                  |
|              | Yan_55_3b| −0.290             | 0.029     | −0.509             | 0.063     |                        |             |                  |                         |             |                  |
|              | Yan_55_3c| −0.307             | 0.028     | −0.449             | 0.063     |                        |             |                  |                         |             |                  |
|              | Yan_55_3d| −0.319             | 0.030     | −0.499             | 0.062     |                        |             |                  |                         |             |                  |
### Table S-1 continued

|          | \(\varepsilon^{53}\text{Cr} \) | s.e. int.\(^a\) | \(\varepsilon^{54}\text{Cr} \) | s.e. int.\(^a\) | \(\varepsilon^{53}\text{Cr} \) mean | 2 s.d. ext.\(^b\) | 2 s.e. ext.\(^b\) (\(n\)) | \(\varepsilon^{54}\text{Cr} \) mean | 2 s.d. ext.\(^b\) | 2 s.e. ext.\(^b\) (\(n\)) |
|----------|-------------------------------|----------------|-------------------------------|----------------|------------------------------------------|----------------|-----------------------------|------------------------------------------|----------------|-----------------------------|
| Duchesne | Duch_55_1c                     | −0.144         | 0.038                         | −0.680         | 0.087                                    | −0.160         | 0.097                       | 0.037 (7)                               | −0.487         | 0.413                       | 0.156 (7) |
|          | Duch_55_1d                     | −0.134         | 0.040                         | −0.753         | 0.086                                    |                |                             |                                          |                |                             |          |
|          | Duch_55_1e                     | −0.203         | 0.044                         | −0.674         | 0.103                                    |                |                             |                                          |                |                             |          |
|          | Duch_55_1f                     | −0.092         | 0.046                         | −0.286         | 0.099                                    |                |                             |                                          |                |                             |          |
|          | Duch_55_1g                     | −0.171         | 0.041                         | −0.509         | 0.084                                    |                |                             |                                          |                |                             |          |
|          | Duch_55_1x                     | −0.249         | 0.050                         | −0.311         | 0.104                                    |                |                             |                                          |                |                             |          |
|          | Duch_55_1xx                    | −0.127         | 0.045                         | −0.198         | 0.104                                    |                |                             |                                          |                |                             |          |
| Standards| IAG OKUM                       |                |                               |                |                                          | 0.020          | 0.159                       | 0.065 (7)                               | 0.083          | 0.270                       | 0.110 (7) |
|          | OKUM_50_1                      | 0.046          | 0.032                         | 0.140          | 0.067                                    |                |                             |                                          |                |                             |          |
|          | OKUM_50_2                      | 0.034          | 0.038                         | 0.204          | 0.081                                    |                |                             |                                          |                |                             |          |
|          | OKUM_50_3                      | 0.013          | 0.029                         | 0.057          | 0.063                                    |                |                             |                                          |                |                             |          |
|          | OKUM_61_1                      | −0.054         | 0.029                         | 0.114          | 0.064                                    |                |                             |                                          |                |                             |          |
|          | OKUM_61_1b                     | −0.106         | 0.029                         | −0.231         | 0.064                                    |                |                             |                                          |                |                             |          |
|          | OKUM_61_2                      | 0.168          | 0.031                         | 0.173          | 0.063                                    |                |                             |                                          |                |                             |          |
|          | OKUM_61_2b                     | 0.036          | 0.031                         | 0.125          | 0.062                                    |                |                             |                                          |                |                             |          |
|          | Allende (CV)\(^c\)            |                |                               |                |                                          | 0.072          | 0.132                       | 0.066 (4)                               | 0.881          | 0.241                       | 0.120 (4) |
|          | All1                           | 0.045          | 0.031                         | 0.967          | 0.061                                    |                |                             |                                          |                |                             |          |
|          | All1b                          | 0.092          | 0.030                         | 0.865          | 0.063                                    |                |                             |                                          |                |                             |          |
|          | All2                           | −0.014         | 0.027                         | 0.691          | 0.054                                    |                |                             |                                          |                |                             |          |
|          | All2b                          | 0.167          | 0.031                         | 1.001          | 0.070                                    |                |                             |                                          |                |                             |          |
|          | Dergaon WR (H5)                |                |                               |                |                                          | 0.117          | 0.078                       | 0.039 (4)                               | −0.380         | 0.244                       | 0.122 (4) |
|          | D_W_63_1                       | 0.057          | 0.031                         | −0.547         | 0.069                                    |                |                             |                                          |                |                             |          |
|          | D_W_63_2                       | 0.138          | 0.035                         | −0.399         | 0.081                                    |                |                             |                                          |                |                             |          |
|          | D_W_63_1b                      | 0.162          | 0.029                         | −0.203         | 0.060                                    |                |                             |                                          |                |                             |          |
|          | D_W_63_1b                      | 0.112          | 0.036                         | −0.371         | 0.080                                    |                |                             |                                          |                |                             |          |
|          | RF 529 WR (Acap)               |                |                               |                |                                          | 0.122          | 0.089                       | 0.045 (4)                               | −0.698         | 0.170                       | 0.085 (4) |
|          | Acap1                          | 0.187          | 0.026                         | −0.677         | 0.058                                    |                |                             |                                          |                |                             |          |
|          | Acap1b                         | 0.077          | 0.026                         | −0.741         | 0.058                                    |                |                             |                                          |                |                             |          |
|          | Acap2                          | 0.138          | 0.029                         | −0.572         | 0.067                                    |                |                             |                                          |                |                             |          |
|          | Acap2b                         | 0.083          | 0.030                         | −0.801         | 0.064                                    |                |                             |                                          |                |                             |          |

\(^a\)s.e. int.: internal error (reported as 1 s.e.) for a single filament run consisted of 24 blocks with 20 cycles each (integration time = 8.389 s).

\(^b\)s.d. ext. and s.e. ext.: external errors of the replicate measurements reported as 2 s.d. and 2 s.e., respectively. \(n\) = number of replicate measurements.

\(^c\)Allende rock standard (Smithsonian standard powder, USNM 3529, Split 18 position 1).

Abbreviations: Daub, daubréelite; Chr, chromite; WR, whole rock; Acap, Acapulcoite.
Table S-2 Weighted mean $\varepsilon^{53}$Cr and $\varepsilon^{182}$W of combined IIAB, IIIAB and IVA groups and corresponding Mn–Cr and Hf–W model ages.

| Sample      | $\varepsilon^{53}$Cr | Mn–Cr Model age (Ma) | Iron meteorite group | $\varepsilon^{182}$W | Hf–W Model age (Ma) |
|-------------|-----------------------|-----------------------|----------------------|----------------------|---------------------|
| Agoudal     | −0.210 ± 0.023         |                       |                      | −3.40 ± 0.03         |                     |
| Sikhote Alin| −0.228 ± 0.025         |                       |                      | −3.35 ± 0.03         |                     |
| NWA 11420   | −0.203 ± 0.045         |                       |                      | −3.32 ± 0.05         |                     |
| Saint Aubin | −0.268 ± 0.029         |                       |                      |                      |                     |
| Cape York   | −0.196 ± 0.043         |                       |                      |                      |                     |
| Yanhuitlan  | −0.272 ± 0.027         |                       |                      |                      |                     |
| Duchesne    | −0.160 ± 0.037         |                       |                      |                      |                     |
| Weighted mean | −0.227 ± 0.006     | 0.03 ± 0.06$^a$       | Weighted mean        | −3.37 ± 0.01         | 1.04 ± 0.09         |
|             |                       | 1.04 ± 0.08$^b$       |                      |                      |                     |

Errors associated with weighted means are given in 1 s.e.
Mn–Cr model ages are determined using $\varepsilon^{53}$Cr$_i = −0.23^a$ and $\varepsilon^{53}$Cr$_i = −0.30^b$ in Equation 1 (see main text). The procedure to determine Hf–W model ages is adopted from Kruijer et al. (2017) and determined using the following equation and parameters:

$$\Delta t = (-1/\lambda) \times \ln \left[ (\varepsilon^{182}W_{\text{sample}} - \varepsilon^{182}W_{\text{chondrites}}/) / \varepsilon^{182}W_{\text{SSI}} - \varepsilon^{182}W_{\text{chondrites}} \right]$$

$\Delta t$ represents the time elapsed since the start of the solar system, $\varepsilon^{182}W_{\text{sample}}$ represents the pre-exposure $\varepsilon^{182}W$ of any iron meteorite group (Kruijer et al., 2017), $\varepsilon^{182}W_{\text{chondrites}}$ is the composition of carbonaceous chondrites (−1.91 ± 0.08) (Kleine et al., 2004), $\varepsilon^{182}W_{\text{SSI}}$ is the solar system initial value of −3.49 ± 0.07 as obtained from CAIs (Kruijer et al., 2014), and $\lambda$ is the decay constant of $^{182}$Hf (0.078 ± 0.002 Myr$^{-1}$, 2σ; Vockenhuber et al., 2004). A better fit between Mn–Cr and Hf–W model ages is obtained when Mn–Cr model ages are determined using $\varepsilon^{53}$Cr = −0.30.

Table S-3 Summary of $(^{53}\text{Mn}/^{55}\text{Mn})_i$ and $(\varepsilon^{53}\text{Cr})_i$.

| $(^{53}\text{Mn}/^{55}\text{Mn})_i$ | $(\varepsilon^{53}\text{Cr})_i$ | References | Method/Approach |
|----------------------------------|-----------------------------|------------|----------------|
| $(8.5 \pm 1.5) \times 10^{-6}$ | $-0.21 \pm 0.09$           | Shukolyukov and Lugmair (2006) | Bulk CC isochron |
| $(6.53 \pm 1.93) \times 10^{-6}$ | $-0.23 \pm 0.11$           | Trinquier et al. (2008b)         | Inner solar system |
| $(6.28 \pm 0.66) \times 10^{-6}$ | $-0.177$                   | Trinquier et al. (2008b)         | Orgueil (CI1) leachates |
| $(9.1 \pm 1.7) \times 10^{-6}$  |                             | Nyquist et al. (2009)            | Best Estimate from $(^{53}\text{Mn}/^{55}\text{Mn})_i$, v.s. $(^{26}\text{Al}/^{27}\text{Al})$, |
| $6.8 \times 10^{-6}$            | $-0.30 \pm 0.05$           | Göpel et al. (2015)              | Bulk CC isochron calibrated against the solar system age |
| (9.1 ± 1.7) × 10⁻⁶             |                            | This study                       | Proposed from combined Mn–Cr and Hf–W chronometry of IIAB, IIIAB and IVA iron meteorite groups |
**Supplementary Figures**

Figure S-1  (a) $\varepsilon^{54}$Cr vs. $\varepsilon^{53}$Cr and (b) Fe/Cr vs. $\varepsilon^{53}$Cr plots for the analysed iron meteorite samples. The black line in (a) shows a linear correlation between excesses in $\varepsilon^{54}$Cr and $\varepsilon^{53}$Cr [$y = (3.90 \pm 0.03)x + (-0.5 \pm 2.6)$ (95% conf.)] determined by Liu et al. (2019) for iron meteorites analysed by Qin et al. (2010), Bonnand and Halliday (2018) and Liu et al. (2019). The error on the correlation line is not shown for the sake of clarity. The $\varepsilon^{53}$Cr and $\varepsilon^{54}$Cr values show no correlation for the analysed chromite/daubréelite fractions, corroborating the negligible spallogenic contribution in these components.
Figure S-2  Mn–Cr model ages plotted on an $\varepsilon^{53}$Cr evolution curve using Equation 1 and solar system initial values of (a) $\varepsilon^{53}$Cr$_i = -0.23$ from Trinquier et al. (2008b) and (b) $\varepsilon^{53}$Cr$_i = -0.30$ as proposed in the present study (see main text for the model age calculation). Different evolutionary paths represent different Mn/Cr ratios of the parent bodies. The trajectories are derived using Equation 1 with the following Mn/Cr ratios: CI chondrites (0.84), H chondrites (0.69), L chondrites (0.76), LL chondrites (0.83), combined OCs (0.74) and combined CC chondrites (0.52) (Zhu et al., 2021). Error bars represent 2 s.e. uncertainties. Model ages for IIAB, IIIAB, and IVA groups are unaffected by the growth trajectory chosen, given current analytical resolution. Assuming a Mn/Cr similar to carbonaceous chondrites would change the model ages by a maximum of 1 Ma for the youngest sample. However, since all samples belong to the non-carbonaceous group, the average composition of OCs is most appropriate.
Figure S-3  Mn–Cr (present study) and Hf–W (Kruijer et al., 2017) core formation ages. Mn–Cr model ages for each sample are determined using solar system initial ε^{53}Cr, and canonical (^{53}Mn/^{55}Mn)_{ss} values taken from Trinquier et al. (2008b; coloured symbols, black borders), Göpel et al. (2015; coloured, no borders), and Shukolyukov and Lugmair (2006; white symbols).
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