The great isotopic dichotomy of the early Solar System

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Summary paragraph

The isotopic composition of meteorites and terrestrial planets holds important clues about the earliest history of the Solar System and the processes of planet formation. Recent work has shown that meteorites exhibit a fundamental isotopic dichotomy between *non-carbonaceous* (NC) and *carbonaceous* (CC) groups, which most likely represent material from the inner and outer Solar System, respectively. Here we review the isotopic evidence for this NC-CC dichotomy, discuss its origin, and highlight the far-reaching implications for the dynamics of the solar protoplanetary disk. The NC-CC dichotomy combined with the chronology of meteorite parent body accretion mandate an early and prolonged spatial separation of inner (NC) and outer (CC) disk reservoirs, lasting between ~1 and ~4 million years (Myr) after Solar System formation. This is most easily reconciled with the early and rapid growth of Jupiter's core, inhibiting significant exchange of material from inside and outside its orbit. The growth and migration of Jupiter also led to the later implantation of CC bodies into the inner Solar System and, therefore, can explain the co-occurrence of NC and CC bodies in the asteroid belt, and the delivery of volatile- and water-rich CC bodies to the terrestrial planets.

1. Introduction

The Solar System formed by the gravitational collapse of a molecular cloud core, which resulted in the formation of a circumsolar disk of gas and dust (sometimes called the 'solar nebula'). This disk was ultimately transformed into a planetary system consisting of a single central star, the Sun, surrounded by four terrestrial planets in the inner Solar System, four giant planets in the outer Solar System beyond the 'snow line', and a multitude of smaller bodies, including asteroids, moons, dwarf planets and comets. To understand how the Solar System evolved towards its present-day configuration, the events and processes occurring during the earliest stages of Solar System history must be reconstructed at a very high temporal and spatial resolution. Although astronomical observations[1] and dynamical modelling[2] provide fundamental insights into the structure and dynamics of protoplanetary disks, and the processes of planetary accretion, the study of meteorites allows reconstructing the Solar System's earliest history with unprecedented resolution in time and space. Recent analytical advances in the precision of isotope ratio measurements not only make it possible to date meteorites at sub-million-year precision[3-5] (see Box 1), but also to identify distinct nucleosynthetic isotopic signatures. This allows genetic links between planetary materials to be determined and helps constrain the area of the disk a given meteorite originated[6-8].

Most meteorites derive from asteroids presently located in the main asteroid belt between Mars and Jupiter (at ~2.0-3.3 au), and have traditionally been viewed as samples from bodies that formed where they are found today. However, recently this perspective has changed dramatically with the discovery of a fundamental genetic dichotomy observed in the nucleosynthetic isotope signatures of *non-carbonaceous* (NC) and *carbonaceous* (CC) meteorites[6,8,9]. This discovery, combined with the establishment of a precise chronology for the accretion of meteorite parent bodies, has enabled the integration of meteoritic constraints into large-scale models of disk evolution and planet formation.

2. The non-carbonaceous–carbonaceous meteorite dichotomy

Nucleosynthetic isotope anomalies arise from the heterogeneous distribution of presolar phases, and ultimately reflect that the Solar System incorporated material from different stellar sources. As evident from analyses of presolar grains contained in primitive meteorites, the Solar System's molecular cloud comprised materials with strongly variable isotopic compositions[10]. Although processes within the Solar System's parental molecular cloud and/or the circumsolar disk homogenized these materials relatively well, small heterogeneities exist that have been sampled at the scale of meteorite components, bulk meteorites, and planets[11]. Nucleosynthetic isotope anomalies have been identified for many elements, but here we will focus on those that are most relevant for the definition of the NC-CC dichotomy and, hence, provide the most detailed insights into the dynamics of the early Solar System.

Meteorites exhibit significant isotope anomalies for elements like O, Cr, and Ti (note that the O isotope anomalies are not nucleosynthetic in origin, but nevertheless are indicative of spatial or temporal changes of solid material in the disk[12]). As such, it is no surprise that the NC-CC dichotomy was first recognized based on isotope anomalies for these three elements[8]. The dichotomy is most clearly observed when different isotope anomalies (e.g., ^{54}Cr vs. ^{50}Ti) are plotted against each other (Fig. 1). In spite of isotope variations among bulk meteorites within each reservoir, there is a clear 'gap' between the NC and CC reservoirs, indicating that there has not been significant mixing of NC and CC materials during the formation of meteorites. Subsequent studies demonstrated that the NC-CC dichotomy extends to other elements, such as Ni[13,14] (Fig. 1d) and Mo[6,9,15,16] (Fig. 2a). Molybdenum is especially useful in identifying the NC-CC dichotomy because it allows anomalies of distinct origins to be distinguished and because, unlike Ti and Cr, the isotopic composition of Mo can be analysed in essentially all meteorites. Specifically, the heterogeneous distribution of carriers enriched in nuclides produced in the slow neutron capture process (*s*–process) of stellar nucleosynthesis and the rapid neutron capture process (*r*–process) results in different patterns of Mo isotope anomalies within individual samples[17]. These variable nucleosynthetic components are most clearly seen in a plot of ε^{95}Mo versus ε^{94}Mo (the parts-per-10,000 deviations of the ^{95}Mo/^{96}Mo and ^{94}Mo/^{96}Mo ratios from terrestrial standard values), where NC and CC meteorites define two separate and parallel *s*-process mixing lines with a resolved offset between the two lines (Fig. 2a). This offset reflects an approximately homogeneous enrichment in *r*-process (and possibly *p*-process[15,16]) nuclides in the CC over the NC reservoir[6,18]. The fact that Mo can be analysed in a wide range of sample types leads to the realization that the NC-CC dichotomy is a fundamental and ubiquitous characteristic of the entire meteorite record.

As will be discussed in more detail below, the NC-CC dichotomy most likely reflects the separation of the early Solar System into an inner and outer disk separated by Jupiter. As carbonaceous chondrites are commonly assumed to have accreted at greater heliocentric distances than ordinary and enstatite chondrites, and because the Earth and Mars plot within the NC field (Fig. 1), the NC reservoir represents the inner and the CC reservoir the outer Solar System[8] (Fig. 5).

3. Meteorite chronology in light of the NC-CC dichotomy

Utilizing the NC-CC dichotomy of meteorites to understand the evolution of the early Solar System and determining whether the dichotomy reflects temporal and/or spatial changes in the isotopic composition of the disk, requires knowledge of the timescales of meteorite parent body accretion. However, parent body accretion cannot be dated directly, but must be inferred either by dating the formation of a specific component (e.g., chondrules) that is closely linked in time to the accretion of their parent body, or alternatively, by dating a specific chemical differentiation process (e.g., core formation), which can be linked to the time of parent body accretion via thermal modelling. Rather than providing a comprehensive summary of the chronology of meteorites, we will here focus on those ages that provide the most precise constraints on the accretion timescales of NC and CC meteorite parent bodies. Below we distinguish between the accretion ages for the parent bodies of differentiated meteorites (Section 3.1) and of chondrite parent bodies (Section 3.2). Note that all ages are given relative to the start of Solar System history 4567.2±0.2 million years (Myr) ago[3,19] as defined by the ages of Ca-Al-rich inclusions (CAIs; see Box 1).

3.1. Differentiated meteorites and the first planetesimals

Differentiated meteorites include samples from the metallic cores (i.e., iron meteorites) as well as silicate mantles and crusts (e.g., angrites, eucrites, ureilites) of differentiated asteroids. Collectively the meteorite ages demonstrate that planetesimal differentiation occurred within the first few million years after CAI formation[20] (Myr), consistent with heating driven mainly by ^{26}Al decay[21]. The most direct evidence for early planetesimal differentiation comes from the Hf-W chronometry of 'magmatic' iron meteorites, which are thought to sample the cores of differentiated protoplanets[22]. The Hf-W model ages of core formation (Box 1) are between ~0.3 and ~1.8 Myr for NC irons, and between ~2.2 and ~2.8 Myr for CC irons[4,9] (Fig. 3b). Combining the Hf-W ages with thermal modelling of bodies internally heated by ^{26}Al decay demonstrates that NC iron meteorite parent bodies accreted less than 0.5 Myr, whereas CC iron meteorite parent bodies accreted less than 1 Myr after CAI formation[4,9] (Fig. 4). Iron meteorite parent bodies, therefore, are among the first planetesimals formed in the Solar System. A corollary of this observation is that rapid formation of differentiated planetesimals (i.e. of iron meteorite parent bodies) was possible not only in the inner-most terrestrial planet region[23], but also in the outer disk (i.e., the CC reservoir).

Accretion timescales can in principle also be inferred for the parent bodies of differentiated achondrites (e.g., angrites, eucrites, ureilites). However, these accretion ages are less well constrained, because there are additional parent-to-daughter (e.g., Hf-W or Al-Mg) fractionation events in the silicate mantles subsequent to core formation. The isotopic compositions of these samples, therefore, reflect more than one differentiation event, making the model ages for core formation more uncertain. Nevertheless, there is general agreement that the angrite and eucrite parent bodies accreted well within the first ~1–2 Myr of the Solar system[24-26], and thus as early as the iron meteorite parent bodies. However, extremely early accretion ages reported for the angrite and ureilite parent bodies[27,28] hinge on the contested[29,30] assumption of a heterogeneous distribution of ^{26}Al in the Solar System, and the ureilite parent body in particular may have accreted slightly later than the parent bodies of other differentiated objects[31]. Regardless of these uncertainties, the chronology of differentiated achondrites indicates that these meteorites, like the irons, derive from an early generation of planetesimals.

3.2. 'Late' accretion of chondrite parent bodies

Chondrites are thought to derive from asteroids that never melted and, therefore, preserved components that formed prior to their accretion. Of these, millimetre-sized igneous spherules know as chondrules are not only the most dominant, but also the most extensively dated component. Different mechanisms for chondrule formation have been proposed, but no consensus about their formation process has yet been reached[32]. Chondrules may have formed by melting of dust aggregates in the solar protoplanetary disk, which might have facilitated the accumulation of dust into planetesimals[33,34]. They may also have formed during protoplanetary impacts and would then merely be a by-product of planet formation[35]. Regardless of their exact formation process, chondrules formed prior to their assembly into chondrite parent bodies, and so dating chondrule formation constrains the timescale of chondrite parent body accretion.

Ages for chondrules are typically obtained either by pooling multiple chondrules (Pb-Pb, Hf-W) or by dating single chondrules (Al-Mg, Pb-Pb). Perhaps the most stringent constraint comes from Al-Mg chronometry of individual chondrules from the least altered chondrites, revealing clear age peaks at ~2-3 Myr (for chondrules from ordinary, CV, and CO chondrites) and at ~3.7 Myr (CR chondrites), after CAI formation[5,36-39] (Fig. 3a). These ages are in excellent agreement with Hf-W[29,34] and Pb-Pb[40-43] ages of pooled chondrule separates from CV and CR chondrites, indicating that the vast majority of chondrules formed between ~2 and ~4 Myr after CAI formation (Fig. 3a). Moreover, chondrules from a given chondrite group formed in a narrow time span of <1 Myr, suggesting they rapidly accreted into their parent bodies. The youngest chondrule ages of ~4–5 Myr are obtained for CB chondrites[44,45], but their formation process likely was different from that of other, more common chondrules[45,46].

Given this consistent picture of chondrule chronology it is surprising that Pb-Pb ages for some *individual* chondrules from a given chondrite group display a spread in ages from ~0–4 Myr, whereas Al-Mg ages remain relatively constant[3,47,48]. One possibility to account for the disparity between Pb-Pb and Al-Mg ages for single chondrules is that ^{26}Al was heterogeneously distributed among the chondrule precursors, and that variations in ^{26}Al abundances, therefore, have no chronological meaning[47,48]. This, however, is not easily reconciled with the good agreement of Hf-W and Al-Mg ages for meteorites[29,30], and with the good agreement between Al-Mg, Hf-W *and* Pb-Pb ages for pooled chondrule separates (Fig. 3a). A heterogeneous ^{26}Al distribution would also lead to an apparent range in Al-Mg chondrule ages, instead of a single well-defined age peak observed for each chondrule group. It should be noted that chondrules for which individual Pb-Pb ages have been reported are exceptionally large[47] and may, therefore, be unrepresentative of the broader chondrule population. The Pb-Pb ages may also be shifted towards older ages due to loss of short-lived ^{222}Rn in the ^{238}U-^{206}Pb decay chain[5]. Thus, in spite of the ancient Pb-Pb ages reported for a few chondrules, there is little doubt that the vast majority of chondrules formed between ~2 and ~4 Myr after CAI formation.

Besides estimates based on chondrule ages, the accretion times of chondrite parent bodies have also been determined using thermal modelling of asteroids heated internally by ^{26}Al decay, combined with either the inferred peak metamorphic temperatures reached inside these bodies[49] or with the chronology of alteration products (e.g., carbonates and secondary fayalites)[50-52]. Using these approaches generally results in accretion ages that are consistent with the isotopic ages of chondrules. For instance, for the CV chondrite parent body the 2.5–3.3 Myr accretion age obtained from thermal modeling[50,51] is in good agreement with the aforementioned CV chondrule ages of 2–3 Myr after CAI formation. For CM chondrites, for which no chondrule ages are available, a 3.0–3.5 Myr accretion age is obtained[52], suggesting that this body formed somewhat later than the ordinary, CV, and CO chondrite parent bodies (Fig. 3a).

In summary, the chronology of chondrules and secondary alteration products in primitive chondrites, as well as thermal modelling of bodies heated by ^{26}Al decay, indicate that chondrite parent body accretion occurred between ~2 and ~4 Myr after CAI formation, and post-dated the accretion of differentiated asteroids. In the NC reservoir, meteorite parent body accretion ceased at ~2 Myr, when the ordinary chondrite parent bodies formed, but in the CC reservoir continued until at least ~3–4 Myr, when the CR and CM chondrite parent bodies formed (Fig. 4).

4. Dynamical implications of the NC-CC dichotomy

Linking the chronology of meteorite parent body accretion with the NC-CC dichotomy provides fundamentally new insights into the dynamics and large-scale structure of the solar protoplanetary disk, the formation and growth history of Jupiter, and the accretion dynamics of terrestrial planets, including the delivery of water and highly volatile species to Earth.

4.1. Origin of the dichotomy and structure of the solar protoplanetary disk

To understand the origin of the NC-CC dichotomy, it is useful to summarize its three key characteristics. First, the dichotomy requires a larger fraction of nuclides produced in neutron-rich stellar environments to be present in the CC reservoir compared to the NC reservoir. This is manifest by enrichments in ^{50}Ti, ^{54}Cr, and *r*-process Mo isotopes in CC materials relative to NC materials. Second, the same isotopic characteristics, but with more pronounced enrichments, are typically also found in 'normal' CAIs[11,53], which are known to have formed very early[3,41,54,55]. Finally, the dichotomy exists for both refractory (e.g., Ti, Mo) and non-refractory elements (e.g., Cr, Ni), which were likely hosted in distinct carriers. Based on these observation two scenarios for the origin of the dichotomy can be ruled out. First, the dichotomy cannot reflect preferential destruction and volatilization of isotopically anomalous material from thermally labile presolar carriers by locally elevated temperatures within the disk, because such 'thermal processing' would have likely resulted in disparate effects on carriers of elements with different volatilities. Moreover, there is no *a priori* reason why thermal processing would solely affect carriers from specific neutron-rich stellar environments, and not also other carrier phases. Second, the dichotomy also cannot solely result from admixing of isotopically anomalous CAIs to the CC reservoir, because CAIs contain too little Cr and Ni to have a significant effect on the isotopic composition of these elements throughout the outer disk[13,56].

Instead, the key characteristics of the dichotomy outlined above are more readily explained if the isotopic difference between the NC and CC reservoirs is inherited from the Solar System's parental molecular cloud and was imparted onto the protoplanetary disk during infall from the collapsing protostellar envelope (Fig. 5). For instance, in a model proposed by Nanne et al. [13,] and Burkhardt et al. [56] the isotopic composition of early-infalling material is characterized by enrichments in nuclides from neutron-rich stellar environments and is similar to that recorded in CAIs, which formed close to the Sun and were subsequently transported outwards by rapid viscous spreading of the disk[57-59]. This earliest disk would not only have contained CAIs but also other, less refractory, dust particles[56]. Later infalling NC material was depleted in nuclides from neutron-rich stellar environments, and provided most of the mass of the inner disk[59]. The model assumes that the outer disk, which had formed by viscous spreading of early infalling material, extended beyond the radius at which the later infalling material is added (Fig. 5). In this case, a signature of the earliest disk would be preserved, in diluted form, as the composition of the CC reservoir, which is intermediate between those of early- (i.e., CAI-like) and late-infalling (i.e., NC-like) material. The strength of this model is that it readily accounts for the formation of CAIs close to the Sun, their subsequent outward transport, and the isotopic link between CAIs and the CC reservoir by the same process, namely the rapid radial expansion of early-infalling material[13]. Finally, an origin of the NC-CC dichotomy during later infall implies that the Solar System's parental molecular cloud was isotopically heterogeneous. It is important to recognize that the magnitude of this isotopic heterogeneity is on the order of only ~0.1%. Such extremely small heterogeneities are not improbable in the large and dynamic structures of molecular clouds.

4.2. The Jupiter barrier

Linking the NC-CC dichotomy (Section 2) with the chronology of meteorite parent body accretion (Section 3) provides key constraints on the formation and growth history of Jupiter. In particular, the chronology of meteorites demonstrates that meteorite parent body accretion in the NC and CC reservoirs commenced very early and continued concurrently for several Myr in both reservoirs[9] (Fig. 4). Importantly, the characteristic Mo isotope signatures of the NC and CC reservoirs did not change significantly during this period, as is evident from the observation that in each reservoir early-formed iron meteorites and later-formed chondrites plot on single *s*-process mixing lines (i.e., the NC- and CC-lines; Fig. 2a). The data allow for some deviations from each line, which may reflect small variations in the characteristic *r*-process signatures of the NC and CC reservoirs, but these differences are small compared to the overall offset between the NC- and CC-lines. Combined, these data indicate that the NC and CC reservoirs co-existed, and maintained their isotopic differences, for several Myr[9].

As is evident from the Hf-W ages for iron meteorites, planetesimal accretion in both the NC and CC reservoirs commenced very early. Consequently, one way to explain the characteristic NC-CC isotopic difference sampled by these objects is that it reflects the rapid accretion of dust into planetesimals with more stable orbits, hampering any further mixing of dust from the NC and CC reservoirs. However, this explanation cannot account for the observation that planetesimals with the same characteristic NC-CC isotopic difference (i.e., the chondrite parent bodies in both reservoirs; Fig. 4) continued to accrete for several Myr, because the rapid radial transport of dust in the disk[60,61] would have homogenized the NC-CC isotopic difference on a much shorter timescale. The prolonged spatial separation of the NC and CC reservoirs, therefore, requires a barrier against radial transport of material. The most likely candidate for this barrier is the formation of Jupiter[21], which would have inhibited the inward drift of most dust particles[62,63], preserving the distinct isotopic compositions of the NC and CC reservoirs. By blocking the sunward drift of dust, the Jupiter barrier also led to a mass-deficient inner Solar System, ultimately resulting in the Solar System's bimodal structure of four smaller terrestrial planets surrounded by four gas giant planets[63].

In detail, the efficiency of the Jupiter barrier depends on the grain size of the dust drifting inwards, and on the size (and hence growth history) of Jupiter. For instance, the Jupiter barrier may have resulted in a strong filtering effect, whereby small dust grains could still pass through, whereas the drift of larger grains was efficiently prohibited[64]. While this process may have resulted in small isotopic changes within the NC reservoir, it evidently did not lead to significant departures of meteorite compositions from the NC-line[18], either because the inward drifting CC dust was not accreted efficiently by NC parent bodies[65] or because the total mass of this material was not sufficient to significantly change the composition of the inner disk[9,18].

Jupiter not only provides the necessary barrier for separating the NC and CC reservoirs, its growth[66] and/or migration[67] also provides a mechanism for the inward scattering of CC bodies into the inner Solar System. This accounts for the co-occurrence of both types of bodies in the present-day asteroid belt, implying that the compositional diversity of main belt asteroids reflects their formation over a wide range of heliocentric distances. Further, the inward scattering of objects from beyond Jupiter's orbit also provides a mechanism for the delivery of CC bodies to the growing terrestrial planets[66].

4.3. Growth history of Jupiter

The standard model for the formation of Jupiter is the core accretion model[68], in which Jupiter's gaseous envelope is accreted onto a 'solid' core of 10-20 Earth's masses ($M_{\oplus}$). Once Jupiter's core reached ~20

$M_\oplus$ it significantly hampered the inward drift of dust grains[62], and when Jupiter reached ~50 $M_\oplus$ it opened a gap in the disk[69], ultimately leading to inward migration[67] of Jupiter and gravitational scattering[66] of bodies from beyond its orbit into the inner Solar System (Fig. 5). Within the framework of this model for Jupiter's formation, and under the assumption that the growth of Jupiter is responsible for the *initial* separation of the NC and CC reservoirs, the timescale of its growth can be estimated from the chronology of meteorite parent body accretion within the NC and CC reservoirs.

The tightest constraint on the timescale of Jupiter's growth is provided by the early accretion times of NC and CC iron meteorite parent bodies. As the characteristic *r*-process Mo isotopic difference between the NC and CC reservoirs did not change significantly after the first planetesimals (i.e., the iron meteorite parent bodies) had formed in each reservoir, Jupiter's core was likely grown to near its final size by the time the oldest NC planetesimals formed, at <0.5 Myr after CAI formation[9]. Such a rapid accretion of Jupiter's core probably requires formation by pebble accretion[68,70,71].

Constraining Jupiter's subsequent growth history is more difficult. In the simplest case, the accretion ages of NC and CC meteorites reflect the period of time over which no mixing between both reservoirs occurred[9]. In this case, dynamical mixing of NC and CC bodies could have only occurred after formation of the youngest CC bodies[9] at ~3.7 Myr after CAI formation[29]. In detail, however, the effect of Jupiter's growth on the composition of the NC and CC reservoirs was likely more complicated. For instance, accretion of CC bodies may still have occurred while Jupiter already scattered earlier-formed CC bodies into the inner Solar System, and so Jupiter may have reached ~50 $M_\oplus$ earlier than ~3.7 Myr after CAI formation. For instance, within the framework of the Grand Tack model[67], Jupiter's migration through the asteroid belt would have terminated planetesimal formation there, so in this case Jupiter would have likely reached a mass of ~50 $M_\oplus$ by ~2 Myr, the accretion age of the youngest NC meteorites (the ordinary chondrites). However, if Jupiter never migrated through the asteroid belt, then planetesimal formation in the NC reservoir may have also terminated through the depletion of gas inwards of Jupiter or because most of the dust had already been locked up in planetesimals. Nevertheless, so far there is no observational evidence suggesting inward scattering of CC bodies during the time of NC meteorite parent body accretion, and so it seems unlikely that Jupiter reached ~50 $M_\oplus$ before ~2 Myr. Note that the earliest observed influx of CC bodies into the inner Solar System is at ~4 Myr, as recorded in the H isotopic composition of eucrites and angrites[72,73]. Consistent with this, angrites dated at ~4–5 Myr after CAI formation[25,74] record the absence of a nebular magnetic field[75], indicating that by this time the nebular gas had dissipated. As Jupiter can only grow to its final size of ~318 $M_\oplus$ in the presence of nebular gas, Jupiter's accretion must have been completed by this time[75]. Taking all these observations together suggests that Jupiter's core of 10–20 $M_\oplus$ accreted within <0.5 Myr, while Jupiter reached ~50 $M_\oplus$ after ~2 Myr, and its final size of ~318 $M_\oplus$ before ~4-5 Myr. This timescale of Jupiter's accretion is consistent with predictions of the core accretion model[68,76].

4.4. Accretion of Earth

The NC-CC dichotomy provides a powerful tool to test different terrestrial planet accretion scenarios, which primarily differ in terms of the extent of radial mixing and the provenance of accreted material[77]. Of particular interest is the amount of CC material accreted by Earth (and other terrestrial planets), because this material derives from the most distant sources and therefore provides the tightest constraints on the extent of radial mixing during terrestrial planet formation. However, for most elements the inferred amount of CC material in Earth is uncertain, because, owing to isotopic variations within the NC reservoir (Fig. 1), it depends on the assumed endmember isotopic compositions of Earth's building material[8]. This situation is different for Mo isotopes, because the amount of CC material accreted by Earth can be determined from the position of Earth's primitive mantle (or bulk silicate Earth, BSE) among the NC- and CC-lines, irrespective of the position of Earth's building material on these lines[18]. That the BSE plots between the NC- and CC-lines (Fig. 2b), therefore, indicates that 30–60% of the BSE's Mo derives from the CC reservoir[18]. As a siderophile (metal-loving) element, the Mo in the BSE predominantly derives from the last 10–20% of accretion, because the Mo from earlier stages has been largely removed into Earth's core[78]. Thus, while these data provide no information on whether Earth accreted CC material during earlier stages, they demonstrate that Earth accreted substantial amounts of CC material late in its growth history.

The last 10–20% of Earth's accretion were strongly influenced by the giant impact that led to the formation of the Moon[79], and by the late veneer; the material added to Earth's mantle after this impact. Budde et al.[18] have shown that the BSE's Mo isotopic composition is best reproduced by either a CC composition of the Moon-forming impactor, or by mixed NC-CC compositions for the impactor and the late veneer. In both cases, the Moon-forming impactor contributed CC material to Earth, implying that this body either was a CC embryo from the outer Solar System, or that it accreted substantial amounts of CC material itself prior to collision with Earth. Either way, the late accretion of CC material to Earth likely also delivered water and highly volatile species to Earth[80,81], suggesting that Earth's habitability is strongly linked to the very late stages of its formation.

5. Open questions and future steps

The discovery of the NC-CC isotopic dichotomy has dramatically changed the way by which meteorites are used for constraining the dynamical evolution of the early Solar System and the nature of planet formation. Despite this success, several important questions remain. The efficiency of the Jupiter barrier for separating the NC and CC reservoirs should be better understood, and the isotopic evolution, if any, of the NC reservoir resulting from the potential inward drift of CC dust remains to be quantified, both in terms of spatial heterogeneity and temporal evolution. A related question is whether the inferred rapid formation of Jupiter's core by pebble accretion is compatible with the limited influx of material from the outer into the inner disk mandated by the preservation of an NC-CC isotopic difference.

Another important future step will be to combine the isotopic evidence for the provenance of accreted material derived from the NC-CC dichotomy with dynamical models of terrestrial planet formation. For instance, a scenario linking the late accretion of outer Solar System material by the Earth to an orbital instability of the gas giant planets around the time of the Moon-forming impact[18,82] remains to be tested. It will also be important to combine the isotopic and dynamical constraints with the known chronology of terrestrial planet formation. For instance, Schiller et al.[65] proposed that Earth accreted a large fraction (~40%) of CC-derived dust from the outer Solar System very early, within the lifetime of the protoplanetary disk (i.e., within ~5 Myr after CAI formation). One implication of this model is that about half of the Earth's mass was accreted by this time. However, the ^{182}Hf-^{182}W chronology of core formation on Earth indicates that such a rapid accretion is only possible for a very high degree of core-mantle re-equilibration during each impact, including the Moon-forming event[83-85]. It is unknown, however, if such high degrees of equilibration have been achieved[86].

Finally, Mars will play a key role in addressing some of these issues, because it likely accreted within the first 10 Myr of the Solar System[87,88]. As such, Mars may have recorded the inward scattering of CC bodies during Jupiter's growth and/or migration but may have also accreted CC-derived dust that passed through the Jupiter barrier. However, the nature, timing, and magnitude of the addition of CC material to Mars has yet to be investigated[89]. Clearly, addressing all these questions will lead to major advances in understanding the early Solar System and the fundamental process of planet formation.

Box. 1: Dating meteorites using isotope chronometers.

Radioactive decay systems used for dating meteorites can be subdivided into long-lived and short-lived chronometers. Of these, the ^{207}Pb-^{206}Pb isotope systems, which is based on the decay of long-lived ^{235}U and ^{238}U, can provide very precise absolute ages for meteorites and their components[3,19,74], as long as they are corrected for variable $^{235}U/^{238}U$ in early Solar System materials[90]. Short-lived radionuclides are isotopes that existed at the beginning of Solar System history but that have since decayed. Hence, their presence in the early Solar System can only be detected by studying the isotopic composition of their daughter isotopes. Important examples of short-lived chronometers that are highly relevant for early solar system chronology include the ^{26}Al-^{26}Mg (half-life: ~0.7 Myr) and ^{182}Hf-^{182}W (half-life: ~9 Myr) systems.

For establishing a precise chronology of the early Solar System, it is useful to define a common reference point, which is typically defined by the formation of the oldest dated solids, known as Ca-Al-rich inclusions (CAIs). These refractory inclusions are thought to have formed close the young Sun[91], and were subsequently transported outwards to the accretion region of carbonaceous chondrites[57,58]. The Pb-Pb age of CAIs of 4567.2±0.2 Myr is generally considered to effectively date the start of Solar System history, or 'time-zero' in cosmochemistry[3,19]. CAIs also have the highest initial $^{26}Al/^{27}Al$ and $^{182}Hf/^{180}Hf$ ratios of any meteoritic material[30,54,55,92], making them pivotal reference points for the Solar System's initial compositions of various decay systems. However, there are also CAIs that lack evidence for live ^{26}Al, and these CAIs are thought to have formed slightly earlier than the more common 'normal' CAIs, prior to injection of ^{26}Al into the Solar System[93-95]. Nevertheless, in early Solar System chronology, ages are generally given as the time elapsed since formation of 'normal' CAIs dated at 4567.2±0.2 Myr.

The Al-Mg system provides very precise relative isochron ages for meteorite components such as CAIs[54,55] and chondrules[5,36,38]. These ages are chronologically meaningful only when ^{26}Al was distributed homogeneously throughout the solar system, which is debated[27-30].

The Hf-W system is widely used to date planetary core formation, both on meteorite parent bodies and on larger bodies like the Earth[83,84]. This is because both Hf and W are refractory elements but have different geochemical affinities during metal-silicate separation. As W is moderately siderophile and Hf strongly lithophile, core-mantle differentiation results in high Hf/W in the mantle, and Hf/W of essentially zero in the core. Hence, the Hf-W system can be used to provide model ages for the timing of core formation in planetary bodies that accreted during the earliest stages of Solar System history (i.e., within the effective lifetime of ^{182}Hf).

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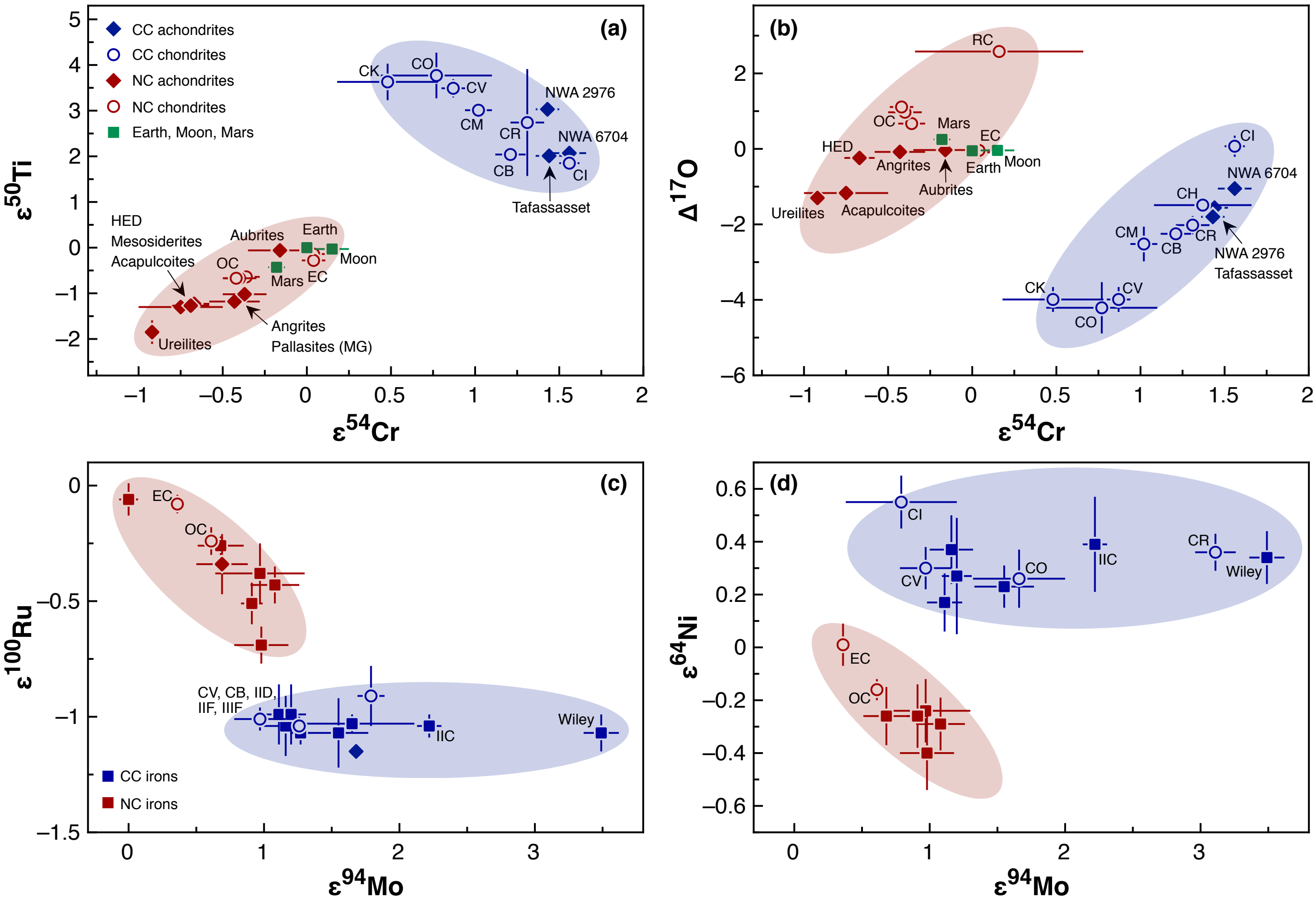

Fig. 1: NC-CC meteorite dichotomy inferred from isotopic signatures of bulk meteorites. (a) ε^{50}Ti *vs.* ε^{54}Cr, (b) Δ^{17}O *vs.* ε^{54}Cr, (c) ε^{100}Ru *vs.* ε^{94}Mo, (d) ε^{64}Ni *vs.* ε^{94}Mo. Note that 1 ε-unit represents the 0.01% deviation (and 1 δ-unit the 0.1% deviation) in the isotopic ratio of a sample relative to terrestrial rock standards. Mass-independent O isotope variations are expressed in Δ^{17}O ($\Delta^{17}O \equiv \delta^{17}O - 0.52\ \delta^{18}O$, where 0.52 is the slope of mass-dependent mass fractionation). Note that Δ^{17}O variations are not nucleosynthetic in origin, but probably reflect photochemical processes in the molecular cloud or the solar nebula[12]. Errors bars denote external uncertainties (2σ) reported in respective studies. The isotopic data plotted here are summarized and tabulated in Ref. 18,56.

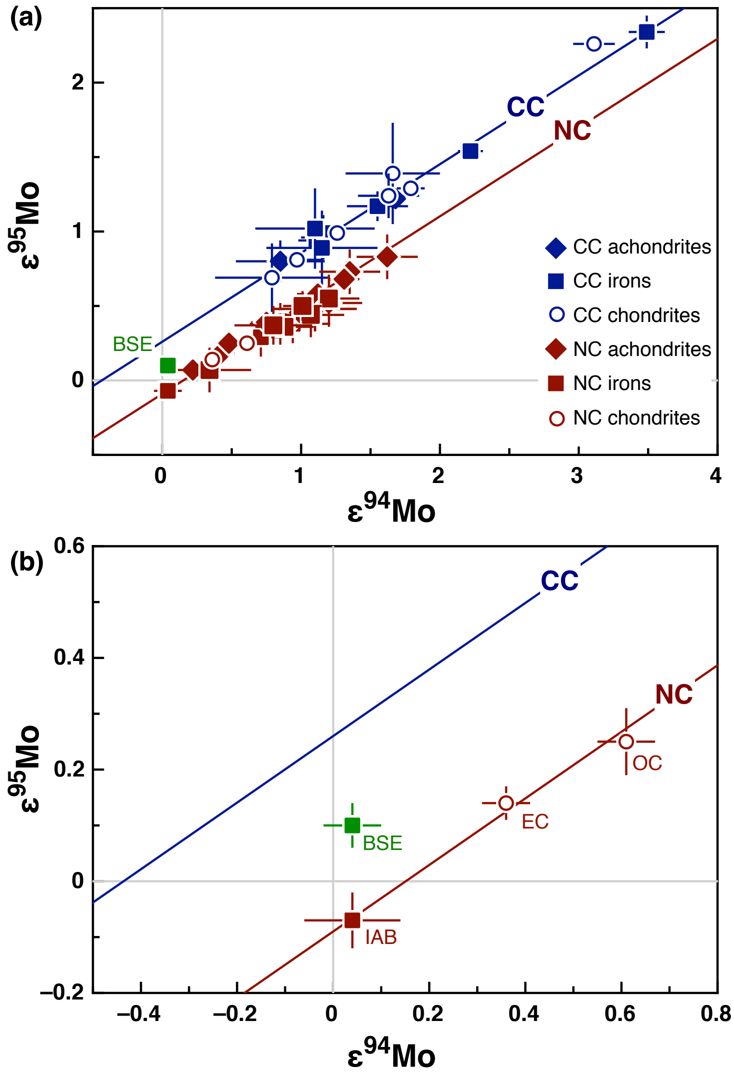

Fig. 2: Molybdenum isotope dichotomy of meteorites. (a) ε^{95}Mo vs. ε^{94}Mo data for bulk meteorites. NC (red) and CC (blue) meteorites define two parallel *s*-process mixing lines with identical slopes, but distinct intercept values[6,9,18]. The offset between the two lines reflects an approximately uniform *r*-process excess in the CC reservoir relative to the NC reservoir. (b) Zoomed-in version of Fig. 2a illustrating that the BSE plots between the NC- and CC-lines. Figure adopted from Budde et al. (Ref.18) and plotted NC and CC lines are based on regression results reported in that study. Error bars denote external uncertainties reported in respective studies (2σ). A summary of the Mo isotopic data shown in the figure is also given in Ref.18.

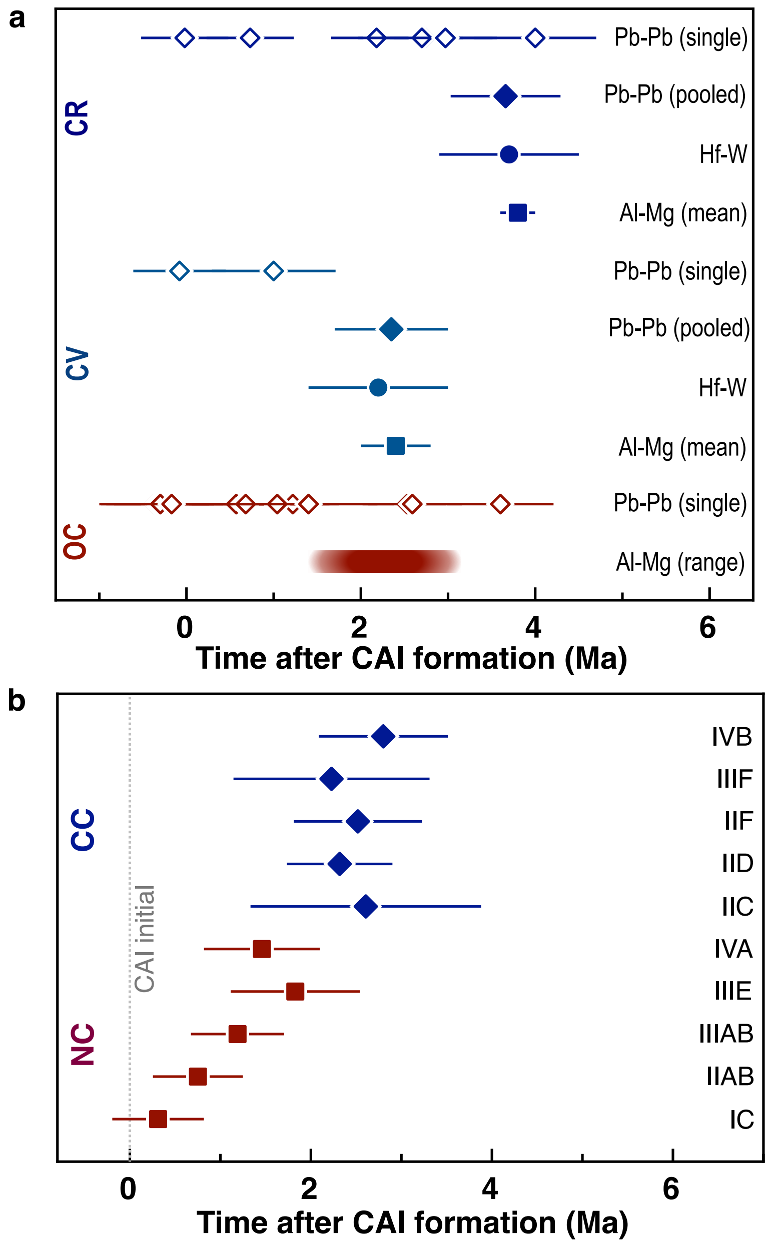

Fig. 3: **Summary of isotopic ages discussed in the text, shown as age intervals relative to CAI formation**. (a) Pb-Pb, Al-Mg, and Hf-W ages of chondrules. Distinguished are Pb-Pb of single chondrules (open symbols; Refs. [3,44]) and pooled chondrule separates (closed symbols; Refs. 40-43), Al-Mg ages of ordinary chondrite (OC) chondrules, CV chondrules, and CR chondrules (Refs. 5,36-39), and Hf-W ages of CV and CR chondrules (Refs. 29,34). Note that absolute Pb-Pb ages were recalculated to age intervals for easy comparison, and all Pb-Pb ages shown are corrected for U isotope variability[90]. (b) Core formation of magmatic iron meteorites based on Hf-W chronometry[4,9]. Distinguished are NC (IC, IIAB, IIIAB, IIIE, IVA) and CC iron meteorite groups (IIC, IID, IIF, IIIF, IVB). Ages for CAIs and Solar System initial values are from Refs. 3,19,30,54.

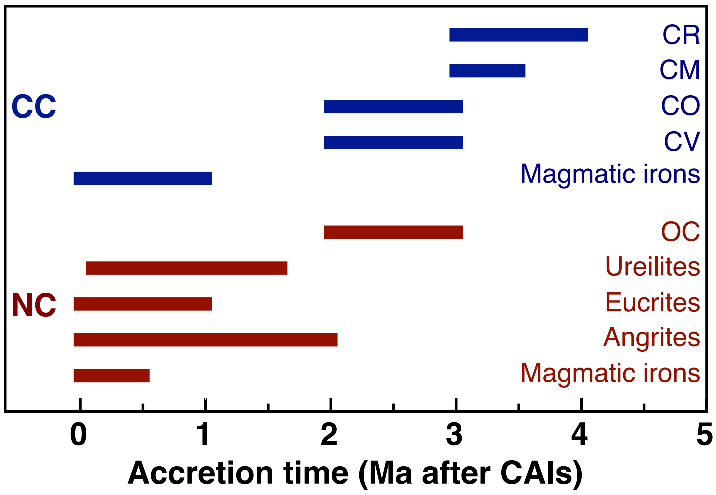

Fig. 4: Accretion timescales of meteorite parent bodies as inferred from isotopic ages of meteorites. Accretion ages of iron meteorite, angrite, and eucrite parent bodies are inferred from model ages for differentiation combined with thermal modelling for internal heating of the parent bodies by ^{26}Al decay (see text). Accretion timescales for chondrite parent bodies are based on Al-Mg, Hf-W, and Pb-Pb ages obtained for chondrules, and on the chronology of alteration products combined with thermal modelling (see text). Note that the horizontal bars reflect the uncertainty of the accretion age estimates, and not the duration of accretion.

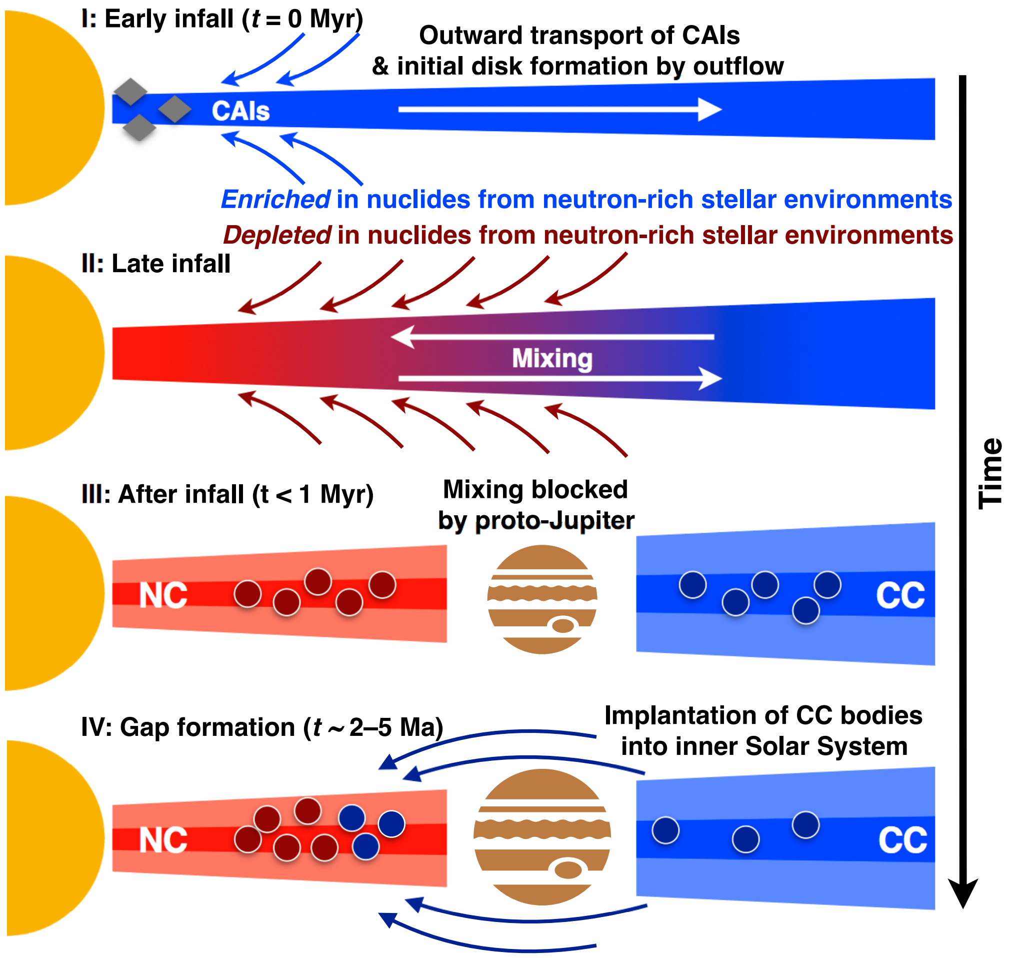

Fig. 5: Evolution of the solar accretion disk. Rapid expansion of early infalling material (I) by viscous spreading produces an initial disk, whose isotopic composition may be recorded in CAIs. Later infalling material (II) was likely more depleted in neutron-rich isotopes (i.e., NC-like). Mixing within the disk likely reduced the initial isotopic difference between solids from the inner and outer disk. The subsequent rapid formation of Jupiter's core (III) likely prevented exchange and mixing of disk materials, thereby maintaining an isotopic difference between the NC and CC reservoirs. Finally (IV) the further growth of Jupiter resulted in the formation of a gap within the disk. This coincided with scattering of CC bodies from the outer disk into the main asteroid belt[66], either through Jupiter's growth on a fixed orbit and/or by inward migration of Jupiter[67]. Figure adopted and slightly modified from Nanne et al.[13].