nature portfolio

Peer Review File

Planetesimal compositions governed by aerodynamic sorting from the onset of Solar System formation

Corresponding Author: Professor Damanveer Grewal

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Comments for the Author)
Nature Astronomy: Review of manuscript from Grewal et al. titled Size-dependent sorting governed planetesimal compositions from the onset of solar system formation
(NATASTRON-26020234)

Overview
This paper presents a novel approach to constrain the matrix fractions of carbonaceous iron meteorite parent bodies (CC IMPBs), with the goal of assessing if the positive correlation between matrix abundance and accretion age inferred for CC chondrite parent bodies extends to the first ~2 Myr of Solar System history, during which the IMPBs formed. The approach relies on the bulk S content and Fe valence states of the IMPBs, inferred via the S concentration and Fe/Ni ratio of their cores (i.e., iron meteorites), respectively, and mass balance. The key finding is that CC IMPBs were matrix-poor, characterized by matrix fractions < 20%, substantially lower than those of CC chondrites. Based on this result, the authors argue that forming CC planetesimals were increasingly matrix-rich across the lifetime of the CC reservoir, not only in its later stages (> 2 Myr following CAIs, when chondrites accreted). The authors further identify the volatile-poor component constituting the bulk of CC IMPBs with mm-scale chondrules, leading to their conclusion that (i) chondrule formation was widespread and early, preceding IMPB formation, and (ii) preferential incorporation of chondrules in planetesimal formation led to the progressive depletion of chondrules in the CC reservoir over time.

Overall Reception
The work constitutes an original step towards a first-order understanding of first-generation planetesimal compositions, a subject which holds significant bearing on models of early Solar System evolution, and therefore of great scientific interest. The manuscript is overall well written, and the approach taken emphasizes the utility of chemical proxies in a field which discourse has, in recent years, been largely centered on nucleosynthetic isotope anomalies. While the main idea of the approach is simple, its execution is founded on a plethora of assumptions that warrant scrutiny and deserve either more explicit mention, or detailed explanation. On the chemistry front, for instance, the string of logic underlying the calculation of IMPB bulk S contents appears to rest heavily on an inference drawn from comparing the MVE signatures of IVB and IID meteorites. This should be more explicitly stated in the main text, and described more quantitatively in the supplementary. Also, the connection between Fe valence state, water-ice abundance, and matrix abundance is vague. On the dynamical front, it is unclear whether mm-scale chondrules were the largest particles present in planetesimal formation. Pebbles consisting of matrix material can conceivably grow to the cm-scale, as typically envisioned in dust coagulation models – pebbles are often described as “fluffy” dust aggregates. The prevalence of chondrules in the Solar System has also been called into question, reflecting as it may a sampling bias in our meteorite collections. These caveats should be discussed, in the supplementary if not the main text. Contents of the supplementary, while clear, call for additional detail/elaboration that will serve to inspire confidence in the methodology.
To summarize, owing to the far-reaching implications of the work presented, along with its novelty, the manuscript merits publication after revision. Below are my specific comments, which address the points raised above among others, and which I hope will contribute to a stronger manuscript.

Specific Comments - Main Text

1. Introduction

Line 33-34: “Chondrules and refractory inclusion abundances decline systematically with increasing matrix fraction.”

This appears obvious – aside from chondrules, CAIs, and AOAs, what else is there (aside from small Fe metal grains, etc.) but matrix? Would remove.

Line 34: “...matrix mass fraction in CC chondrites increases”

The authors state this plainly, indicating the matrix-accretion age correlation is well-established and robust. The uncertainties in accretion ages from Hellmann et al. (2023) are so large that those of CI, CM, CR, and Tagish Lake parent bodies are indistinguishable. Moreover, those of CO and CV are indistinguishable as well. I suggest using softer language.

Line 44-45: “...to accrete into planetesimals before very fine-grained (nm-scale) matrix dust”.

In models of dust coagulation in protoplanetary disks, dust particles are often envisioned as mm- to cm-sized aggregates that (i) themselves consists of fine-grained particles (micron-scale), and (ii) limited in growth by fragmentation or radial drift (e.g., Birnstiel et al., 2012). Thus, is it not possible that matrix is held in pebbles with characteristic sizes similar to, or exceeding, mm-scale chondrules? While they are made of smaller grains, the dynamics of such pebbles (i.e., incorporation into planetesimals during hydrodynamic instabilities), is governed by their characteristic size. In this case, the size-sorting argument is severely weakened. Please elaborate.

Line 48: “...gas-rich disk… already forming.”

What is meant by “dynamically active” - the disk evolves across its entire lifetime. Please clarify. Also, please clarify what the authors mean by “gas-solid coupling… [was] most efficient.”

Line 95: “...as water is the principal oxidant in CC planetesimals.”

The link between oxidation state and water abundance warrants caution. Condensation in the presence of dust enrichment can yield oxidized condensates (e.g., Ebel & Grossman, 2000). The authors later discuss how dust enrichment in pressure maxima facilitate both chondrule and planetesimal formation.

2. Sulfur constraints on matrix fractions in CC IMPBs

Lines 120-124: “Sulfur, itself an MVE,...”

The approach using inferred bulk S contents appear to rely heavily on the assumption that S-depletion primarily reflects proto-core segregation, and not volatile loss. This itself is based on the comparison between IVB and IID groups, correct? How well is the impact of S on HSE fractionation constrained? I suggest adding a statement or two here for clarification, given the importance of this step in the modeling.

Overall comment - Fig. 3.

The data resembles more of a step function than a correlation line. Isn’t this more easily explained by extensive volatile (S) loss from IMPBs? Moreover, it should be noted that the data do not preclude CC IMPBs having the same matrix fraction as CO and CV chondrite parent bodies → the error bars are 1SEs, weakening the argument for a systematic increase in matrix fraction over time. I recommend the authors add a paragraph discussing this caveat and alternative explanations than the one they are pushing for.

3. Fe redox constraints on matrix fractions in CC IMPBs

Lines 162-163: “Thus,... matrix abundance.”

Here or earlier on, I think the relationship between oxidation state, water-ice abundance, and matrix abundance needs to be explained in more detail. Are the authors arguing that, since water-ice leads to production of secondary mineral phases that add to the matrix, accreted water-ice and accreted matrix are interchangeable, both leading to an increase in Fe valence state? Please clarify.

Lines 179-180: “By isolating… variable S contents.”

Presumably, this is true under the assumption that CC IMPBs were characterized by similarly low redox potential?

Lines 188-189: Typo → Fig. 2 has no A and B.

Line 209: In the statement “... Fe oxidation states of the latter,” I believe the authors mean “the former” given that the ensuing discussion relates to the CC chondrites.

Discussion

4.1 Matrix-age correlation from the onset of solar system formation

Lines 240-244: “In a gas-rich disk,... later accretion of matrix-rich planetesimals.”

As mentioned above, it is possible that mm- to cm-scale pebbles are instead dust aggregates that constitute the matrix, in which case the argument for chondrule depletion via size-sorting accompanying planetesimal formation breaks down. Please elaborate.

Lines 244-247: “The operation of… planetesimals in extrasolar systems.”

The preferential incorporation of high-Stokes number particles in the streaming instability has never been confined to the Solar System context, but already seen as a general feature of the instability. The comment on extrasolar systems is vague. Please rephrase to add more clarity as to what the authors mean, or remove.

Lines 255-260: “The matrix-age correlation… heating for core formation.”

Why do NC IMPBs, which accreted around the same time as CC IMPBs, have S-rich cores? Based on earlier work by the leading author (Grewal et al., 2024), redox conditions for both NC and CC IMPBs ought to be similar, suggesting both formed beyond the snowline. Is the implication that NC IMPBs accreted with much more matrix than their CC counterparts?

Lines 264-265: “Based on… within the CC reservoir,...”

The CR and IIC parent bodies may have derived from the same local isotopic reservoir, but how does one explain the lack of evolution in the matrix mass fraction within that reservoir over ~2.5 Ma? Doesn’t this argue against the argument of chondrule depletion over time? The following statement of “...reflecting accretion from precursor materials distinct… second generation of chondrules” is a regurgitation of words from Hellmann et al. (2023). Here the “distinct precursor materials” is kept vague, but in the following section, the observation that “no alternative population of MVE-depleted, mm-sized aggregates” is known besides chondrules is used to support the claim that chondrules must be the volatile-poor component. Please elaborate.

4.2 Early onset of widespread chondrule formation

Lines 281-283: “Second,... size-dependent sorting.”

Once again, can one exclude the (likely) possibility that matrix material was held in mm- to cm-scale pebbles?

Lines 283-285: “Third,... non-matrix fraction.”

This does not strike me as a “line of evidence,” but merely a statement amounting to: what else could it be? Please rephrase.

Lines 288-293: “Within this framework,... chondrule-forming epoch.”

Are early formed chondrules more prevalent in NC chondrites, and if so, how does that observation fit into this framework?

Lines 308-311: “Independent corroboration… disk evolution.”

Please clarify this statement → silicate condensation and chondrule formation are different processes.

Methods

Lines 602-604: “Because this S depletion… models.”

Given the significance of this step in calculating the bulk S content, and for the manuscript to be self-constained, I recommend the authors provide more detail into how this recovery is accomplished.

Lines 726-731: “From the core S content, … silicate mantle.”

As above, I recommend the authors provide more detail into how this is done, with numbers (perhaps taking one of the CC IMPBs as an example). This will help those interested in validating the calculations for themselves.

Line 791: Add “S” after “wt.%”.

Reviewer #2

(Comments for the Author)
Dear Editor,

I have completed my review of the manuscript entitled "Size-dependent sorting governed planetesimal compositions from the onset of solar system formation" by Grewal et al. In this study, the authors present new calculations to estimate the bulk S content of carbonaceous iron meteorite parent bodies, as well as the valence state of Fe excluding sulfide contributions. Based on these approaches, they conclude that IMPBs accreted a larger proportion of non-matrix components, implying that efficient size-dependent sorting operated during the earliest stages of Solar System formation.

Overall, the manuscript is well written, and I appreciate both the motivation and the novelty of the calculations. However, I have identified a conceptual issue, essentially a logical assumption, that should be more carefully addressed before the manuscript can be considered for publication.

The authors estimate the fraction of matrix-like material accreted into IMPBs using Eq. 1. To robustly constrain this relationship, three key parameters must be well defined: (1) the bulk S content of IMPBs, (2) the S content of the matrix component, and (3) the S content of the non-matrix component. While I find the authors' approach to estimating the bulk IMPB S content and the non-matrix endmember generally convincing, I have concerns regarding the use of CI chondrites (corrected for terrestrial contamination) as the matrix endmember.

Specifically, it is unclear whether the matrix phase in late-accreting parent bodies is chemically representative of matrix material present during the earliest stages of Solar System formation. Given that aerodynamic sorting is a pervasive process in the protoplanetary disk, it is reasonable to expect that the composition of residual matrix material evolved over time. If so, the S content of the matrix endmember adopted here may not be applicable to early-accreted bodies such as IMPBs.

More broadly, sorting in the early Solar System was likely coupled with continuous recycling of dust. Considering that the total dust mass in the disk was substantially larger than that ultimately incorporated into chondrite parent bodies, it is plausible that such processes could have progressively modified the chemical composition of the residual matrix. For example, S could have become enriched in the remaining fine-grained component as dust mass decreased. Under such a scenario, the authors' conclusion that IMPBs accreted volatile-poor material may still hold, but it would not necessarily require a higher proportion of non-matrix components; instead, it could reflect temporal evolution in matrix composition.

This concern also extends to the Fe valence proxy. The authors' interpretation relies on the implicit assumption that matrix components in both early- and late-accreting parent bodies contained comparable amounts of water (ice) and underwent similar degrees of aqueous alteration. However, this assumption may not be valid. Early accreting parent bodies likely experienced shorter timescales before differentiation, collision, or growth into larger bodies, potentially limiting the duration and extent of aqueous alteration. As a result, Fe valence may be, at least in part, a time-dependent parameter rather than solely a function of matrix abundance.

In summary, the manuscript would benefit from a more thorough assessment of whether matrix-like components remained chemically consistent through time. Without adequately justifying this assumption, the interpretation linking S content and Fe valence directly to matrix fraction-and, by extension, to early sorting processes-remains uncertain.

Minor comments:
Line 129: The variables in Eq. 1 should be clearly defined in the text.
Line 604: More detail should be provided on how bulk S contents of IMPBs are estimated using HSE-based models.
Line 615: The sensitivity of Cbulk to variations in the parameter r should be discussed.

Version 1:

Reviewer comments:

Reviewer #1

(Comments for the Author)
Nature Astronomy: Response to revised manuscript from Grewal et al. titled Aerodynamic sorting governed planetesimal compositions from the onset of solar system formation
(NATASTRON-26020234)

Overall Reception

The authors have addressed most of my concerns to a satisfactory degree. I particularly appreciate their clarification of the logic underlying the calculation and use of IMPB bulk S contents, as well as the relationship between matrix abundance and Fe oxidation state. Below, I provide several final concerns/suggestions intended to strengthen the manuscript for publication.

General Comments

Dynamic argument: Differential delivery + fragmentation rates

Regarding differential delivery rates, it is important to clarify that for a given particle size, denser particles such as chondrules drift inwards faster than low-density aggregates of matrix grains. I agree with the authors that mm-sized chondrules would drift faster than matrix monomers, but again, the transport of matrix material is not controlled by monomer size → pebbles composed of matrix can be cm-scale, exceeding the size of chondrules and drifting inwards faster despite the density contrast. The second mechanism, that of differential fragmentation in pressure bumps, seems more robust.

Additionally, is it assumed that CC IMPBs accreted in a pressure bump, as is believed for CC chondrite parent bodies? The authors should clarify if this is the envisioned scenario. If so, is there a correlation between the matrix fraction of IMPBs and their nucleosynthetic isotopic composition – reflecting an evolution in dust heritage at the pressure bump? Please elaborate.

Argument regarding higher S contents in NC chondrules

The authors argue in their response that NC chondrules are less S-depleted and could thus produce S-rich cores even at low matrix fractions. This should be included in the main text.

Specific Comments

Lines 20 & 102: relationship between Fe oxidation/valence state and water-ice content

As the authors have noted, the Fe valence state reflects both the incorporation of water-ice and pre-accretionary oxidized precursors, both falling under the umbrella of matrix material. I suggest modifying these two lines to reflect the contribution of the latter.

Line 56: "... gas surface densities were at their highest…"

What is the significance of high gas surface densities here? Would remove if unjustified.

Lines 258-261: "The gap probably… future work."

What is the source for the claim that the achondrite parent bodies accreted during the intervening ~1 to 2.5Ma interval? Presumably some achondrites represent the mantles of the IMPBs considered here.

Line 286: "... the CR-IIC case likely reflects…"

I suggests softening the language to "possibly reflects" or "may reflect."

Line 289: "... wherever volatile-poor… local solid reservoir"

I would remove this phrase, and modify the sentence slightly to: "In either scenario, matrix fractions could remain low."

Reviewer #2

(Comments for the Author)
The authors have successfully addressed all of my concerns and those of the other reviewer. The paper is now well-polished, and I am happy to recommend its acceptance for publication

We thank the editor and reviewers for their thorough and constructive evaluation. Below we address each comment in detail. Reviewer comments are shown in black; quoted text from the revised manuscript is shown in blue italics. All lines numbers correspond to the file with marked changes.

We have revised the title from "~~Size-dependent~~ sorting governed planetesimal compositions from the onset of solar system formation" to "*Aerodynamic* sorting governed planetesimal compositions from the onset of solar system formation." This change reflects the revised discussion of the physical sorting mechanism (Sections 4.1 and 4.3), which, in response to reviewer feedback, now encompasses not only Stokes number-governed differential concentration but also differential fragmentation and aerodynamic filtering of mechanically distinct dust components in disk substructures. "Aerodynamic sorting" more accurately captures the full range of physical processes responsible for the observed compositional fractionation than the original "size-dependent sorting," which could be interpreted as implying sorting by particle size alone.

We note that since our original submission, a directly relevant study by Gurrutxaga, Drążkowska, et al. (2026), "Carbonaceous Chondrites provide evidence for late-stage planetesimal formation in a pressure bump," has been posted on arXiv (doi:10.48550/arXiv.2604.16604) and is scheduled for publication in The Astrophysical Journal on May 21, 2026 – well ahead of the publication timeline for the present manuscript. This study provides the numerical framework for the two-mechanism aerodynamic sorting model (differential delivery rates and differential fragmentation in pressure bumps) that we added in our revised Discussion.

Reviewer #1 (Comments for the Author):

Nature Astronomy: Review of manuscript from Grewal et al. titled Size-dependent sorting governed planetesimal compositions from the onset of solar system formation (NATASTRON-26020234)

Overview
This paper presents a novel approach to constrain the matrix fractions of carbonaceous iron meteorite parent bodies (CC IMPBs), with the goal of assessing if the positive correlation between matrix abundance and accretion age inferred for CC chondrite parent bodies extends to the first ~2 Myr of Solar System history, during which the IMPBs formed. The approach relies on the bulk S content and Fe valence states of the IMPBs, inferred via the S concentration and Fe/Ni ratio of their cores (i.e., iron meteorites), respectively, and mass balance. The key finding is that CC IMPBs were matrix-poor, characterized by matrix fractions < 20%, substantially lower than those of CC chondrites. Based on this result, the authors argue that forming CC planetesimals were increasingly matrix-rich across the lifetime of the CC reservoir, not only in its later stages (> 2 Myr following CAIs, when chondrites accreted). The authors further identify the volatile-poor component constituting the bulk of CC IMPBs with mm-scale chondrules,

leading to their conclusion that (i) chondrule formation was widespread and early, preceding IMPB formation, and (ii) preferential incorporation of chondrules in planetesimal formation led to the progressive depletion of chondrules in the CC reservoir over time.

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Overview Point 1: S calculation logic (IVB-IID comparison)

On the chemistry front, for instance, the string of logic underlying the calculation of IMPB bulk S contents appears to rest heavily on an inference drawn from comparing the MVE signatures of IVB and IID meteorites. This should be more explicitly stated in the main text, and described more quantitatively in the supplementary.

We agree that this logical chain was insufficiently explicit. The core argument is as follows: both IVB and IID cores are inferred to be essentially S-free from fractional crystallization modeling. However, IVB shows anomalous MVE depletion (diagnostic of catastrophic volatile loss) while IID does not, suggesting that S-poor cores can arise independently of volatile loss through an independent mechanism. The mechanism – proto-core segregation during protracted core formation (Grewal et al. 2025) – is identified by a distinctive HSE fractionation pattern shared by all four S-poor CC groups (IVB, IID, IIF, IIIF). The reconstructed progenitor core S contents are independently validated by the two CC IMPB groups unaffected by proto-core loss (IIC, SBT), whose primary S contents fall in the same range.

We have added an explicit statement of this logic in the main text (Section 2): "*This S reconstruction is validated by the internal consistency between CC IMPB cores unaffected by proto-core loss (IIC, SBT), which preserve primary S contents and normal HSE systematics, and S-corrected cores (IVB, IID, IIF, IIIF) whose progenitor S contents were recovered using experimentally calibrated HSE partitioning models (see Methods Section 1).*" (lines 131-135)

We have expanded the Methods Section 1 with quantitative details: "*Specifically, the recovery uses equilibrium partitioning models between S-free solid metal restite and S-bearing metallic liquid[28]. Partition coefficients for HSEs, Ni, and Co between solid and liquid metal are strongly dependent on the S content of the liquid[38,66,67], with refractory HSEs (Os, Re, Ir, Ru, Pt) becoming* *increasingly compatible in the solid as liquid S content increases. By fitting the observed abundance patterns of these elements in the restite cores using a Bayesian MCMC approach, both the S content of the segregated proto-core liquid and the mass fraction of extracted liquid are constrained simultaneously*[28]." (lines 671-677)

More details in Methods Section 1: "*Fractional crystallization models indicate that the IVB core was essentially S-free*[29,38,64]*, and IVB also shows anomalous depletion in Ga (0.24 µg/g) and also shows anomalous depletion in Ga and Ge relative to all other CC cores (up to ~2-3 orders of magnitude), attributed to catastrophic volatile loss*[31,32]*. However, the IID core, which is equally S-free from fractional crystallization modeling*[28,61]*, shows no such MVE depletion: its Ga and Ge concentrations are comparable to S-bearing CC cores like IIC*[28]*. This decoupling demonstrates that S-poor core compositions can arise independently of the volatility-correlated MVE depletion seen in IVB*." (lines 648-654)

We have added a worked example using the IVB group: "*We illustrate this procedure using the IVB group. Proto-core segregation models indicate that ~82% of the initial metal segregated as a proto-core liquid containing ~10.6 wt% S, leaving an 18% S-free solid restite – the component sampled by IVB iron meteorites*[28]*. The progenitor core S content is recovered by mass balance:* $0.18 \times 0 + 0.82 \times 10.6 = \sim 9$ *wt% S."* (lines 682-685)

<u>Overview Point 2: Fe valence-water-matrix connection</u>

Also, the connection between Fe valence state, water-ice abundance, and matrix abundance is vague.

We have significantly expanded this explanation in the revised Section 3. The connection operates through two mechanistically distinct pathways, both of which scale with matrix abundance:

Pathway 1 – Water-ice delivery: Alexander (2019) demonstrated that the H_2O/matrix mass ratio is approximately constant across CC chondrites, meaning matrix is the primary carrier of water-ice. Higher matrix fractions deliver proportionally more ice, which upon melting drives aqueous alteration of metallic Fe, irreversibly oxidizing it as H_2 escapes.

Pathway 2 – Pre-accretionary oxidized silicate precursors: Matrix contains Fe-bearing amorphous silicates already partially oxidized before accretion, as directly demonstrated by Ryugu sample analyses and CR chondrite matrices. These phases contribute Fe^{2+} and Fe^{3+} directly to the bulk Fe valence budget independently of aqueous alteration.

Thus, matrix is the carrier of both water-ice (the primary oxidizing agent) and pre-accretionary oxidized Fe-bearing amorphous silicates, so that matrix fraction controls the total oxidized Fe inventory. The non-matrix component (Type I chondrules) contributes metallic Fe and Fe-poor silicates, even when formed in dust-enriched environments.

The revised text in Section 3 now reads:

"This trend arises because matrix is the principal carrier of both oxidizing agents (water-ice) and oxidized Fe-bearing silicate precursors. Higher matrix fractions delivered systematically more water-ice – because ice was intimately associated with fine-grained matrix dust at an approximately constant ice-to-matrix ratio across CC chondrites[2] – driving greater Fe oxidation during parent body alteration. In addition, the matrix likely contained Fe-bearing amorphous silicate precursors that were already partially oxidized before accretion[44–46]. Both sources of oxidized Fe scale with matrix abundance, so increasing matrix content results in higher V_{Fe}^{bulk} values regardless of their relative contributions. Conversely, the non-matrix component in CC chondrites is dominated by Type I chondrules composed of Fe-poor silicates and Fe metal[44–46], which contribute minimal oxidized Fe." (lines 176-185)

Overview Point 3: Dust pebbles vs. chondrules

On the dynamical front, it is unclear whether mm-scale chondrules were the largest particles present in planetesimal formation. Pebbles consisting of matrix material can conceivably grow to the cm-scale, as typically envisioned in dust coagulation models – pebbles are often described as "fluffy" dust aggregates.

We appreciate the reviewer raising this important point. We agree that mm-scale chondrules were likely not free-floating pebbles in the early disk, and our revised manuscript no longer implies this. Recent numerical simulations of multi-component dust evolution in a pressure bump (Gurrutxaga et al. 2026) demonstrate that compositional fractionation between chondrule-like and matrix-like material arises through two complementary mechanisms that do not require individual chondrules to behave as pebbles:

(1) Differential delivery rates: chondrules and refractory inclusions, being denser and on average larger than matrix monomers, have higher Stokes numbers and drift to planetesimal-forming regions at higher rates than matrix dust, depleting the outer disk in rigid components over time.

(2) Differential fragmentation: within pressure bumps, pebbles undergo continuous coagulation-fragmentation cycles. Individual chondrules resist fragmentation below their monomer size, whereas matrix aggregates fragment to micron-sized grains that re-couple to the gas and leak out of the trap. The largest pebbles, those preferentially incorporated into planetesimals via streaming instability, are consequently enriched in rigid, volatile-poor components.

Both mechanisms produce planetesimals that are systematically enriched in chondrule-like material relative to the ambient dust, consistent with the matrix-poor, volatile-depleted compositions we infer for CC IMPBs. Importantly, these mechanisms operate on mixed chondrule-matrix aggregates rather than individual chondrules, directly addressing the reviewer's concern about whether mm-scale chondrules alone could serve as pebbles.

The chemical evidence provides independent corroboration: even if matrix dust coagulated into cm-scale pebbles (Birnstiel et al. 2012), such aggregates would retain volatile-rich, CI-like compositions (~5.3 wt% S, Fe^{3+}/Fe_T). A planetesimal built from such material would exhibit bulk S contents and Fe valence states comparable to CI chondrites – the opposite of what we observe for CC IMPBs (bulk S = 0.6-1.1 wt%, V_{Fe}^{nS} = 0.7-1.6)). The two independent proxies thus confirm that the dominant accreted material was volatile-poor regardless of its physical form.

We have revised the Introduction and Discussion to reflect this understanding.

In the Introduction, we now frame the sorting mechanism broadly: *"This temporal trend likely reflects aerodynamic sorting in the disk, where compact, chondrule-rich material was preferentially accreted relative to porous, fine-grained matrix [4]. This fractionation can arise from contrasts in Stokes number [9–11], which scales with the product of internal particle density and size, and from the differential response of mechanically rigid and fragile dust components to collisional fragmentation and aerodynamic filtering in disk substructures[12]. Both processes favor the preferential incorporation of chondrule-rich material into planetesimals."* (lines 48-53)

In Section 4.1, the mechanistic discussion has been similarly revised to encompass both Stokes number-governed differential concentration and differential fragmentation/filtering: *"This fractionation can arise from contrasts in aerodynamic behavior between compact, volatile-poor and porous, volatile-rich dust components – whether through Stokes number-governed differential concentration or differential fragmentation and filtering in disk substructures. The chemical evidence presented here provides the first empirical demonstration that such compositional fractionation was realized from the onset of planetesimal accretion in the solar protoplanetary disk."* (lines 275-280)

<u>Overview Point 4: Chondrule prevalence and sampling bias</u>

The prevalence of chondrules in the Solar System has also been called into question, reflecting as it may a sampling bias in our meteorite collections.

The apparent scarcity of early-formed chondrules in the CC chondrite record likely reflects a sampling/preservation bias, and our manuscript makes this argument explicitly. Early chondrules were preferentially incorporated into rapidly accreting CC IMPBs where subsequent differentiation erased all textural memory, while later-forming undifferentiated bodies preserve only the younger portion of a prolonged chondrule-forming epoch. The chemical evidence presented here, that CC IMPBs accreted 83-92% volatile-poor material by mass, provides independent support for this interpretation. This preservation bias framework is discussed in Section 4.3.

Given the length limits, we believe the original statements in the paper are suffice to relay this message "*The apparent scarcity of early-formed chondrules in the CC chondrite record likely reflects preservation bias rather than delayed onset of chondrule production. Early chondrules were preferentially incorporated into rapidly accreting CC IMPBs where subsequent differentiation erased all textural memory, while later-forming undifferentiated bodies preserve only the younger portion of a prolonged chondrule-forming epoch.*" (lines 332-336)

These caveats should be discussed, in the supplementary if not the main text. Contents of the supplementary, while clear, call for additional detail/elaboration that will serve to inspire confidence in the methodology.

We have addressed this through multiple additions to both the main text and Methods, as detailed in our responses above.

To summarize, owing to the far-reaching implications of the work presented, along with its novelty, the manuscript merits publication after revision. Below are my specific comments, which address the points raised above among others, and which I hope will contribute to a stronger manuscript.

Specific Comments - Main Text

1. Introduction

Line 33-34: "Chondrules and refractory inclusion abundances decline systematically with increasing matrix fraction."

This appears obvious – aside from chondrules, CAIs, and AOAs, what else is there (aside from small Fe metal grains, etc.) but matrix? Would remove.

Agreed. The sentence has been removed from the revised manuscript.

Line 34: "...matrix mass fraction in CC chondrites increases"
The authors state this plainly, indicating the matrix-accretion age correlation is well-established and robust. The uncertainties in accretion ages from Hellmann et al. (2023) are so large that those of CI, CM, CR, and Tagish Lake parent bodies are indistinguishable. Moreover, those of CO and CV are indistinguishable as well. I suggest using softer language.

Agreed. We have softened the language: "increases" has been changed to "*broadly* increases," and we now explicitly note that accretion ages "*carry large uncertainties*." The relative accretion sequence remains robustly constrained by peak metamorphic temperatures, which we emphasize is the key observational basis.

Line 44-45: "...to accrete into planetesimals before very fine-grained (nm-scale) matrix dust".

In models of dust coagulation in protoplanetary disks, dust particles are often envisioned as mm- to cm-sized aggregates that (i) themselves consists of fine-grained particles (micron-scale), and (ii) limited in growth by fragmentation or radial drift (e.g., Birnstiel et al., 2012). Thus, is it not possible that matrix is held in pebbles with characteristic sizes similar to, or exceeding, mm-scale chondrules? While they are made of smaller grains, the dynamics of such pebbles (i.e., incorporation into planetesimals during hydrodynamic instabilities), is governed by their characteristic size. In this case, the size-sorting argument is severely weakened. Please elaborate.

Addressed comprehensively in our response to the pebble concern above (Overview Point 3). In the revised Introduction, we no longer frame the sorting as operating on individual chondrules versus matrix grains. Instead, the revised text describes two complementary mechanisms – Stokes number-governed differential delivery and differential fragmentation of mechanically rigid versus fragile dust components in disk substructures – both of which operate on mixed chondrule-matrix aggregates and produce planetesimals enriched in volatile-poor material, consistent with our chemical observations.

Line 48: "...a… already forming."

What is meant by "dynamically active" - the disk evolves across its entire lifetime. Please clarify. Also, please clarify what the authors mean by "gas-solid coupling… [was] most efficient."

We agree this phrasing was imprecise. Both phrases have been replaced with physically precise language: *"...gas surface densities were at their highest[15], and the earliest planetesimals were already forming[18,19]."* (lines 56-57)

The phrase "~~gas-solid coupling and aerodynamic size-sorting were most efficient~~" has been removed.

Line 95: "...as water is the principal oxidant in CC planetesimals."

The link between oxidation state and water abundance warrants caution. Condensation in the presence of dust enrichment can yield oxidized condensates (e.g., Ebel & Grossman, 2000). The authors later discuss how dust enrichment in pressure maxima facilitate both chondrule and planetesimal formation.

We agree that the relationship between oxidation state and water abundance warrants careful treatment. However, we note that CC chondrules are overwhelmingly dominated by Type I (FeO-poor) compositions, and that the FeO budget in CC chondrites is predominantly hosted in the matrix component (Alexander 2019). In the revised manuscript, we have the observational constraint that CC chondrules are Type I and contribute minimal oxidized Fe to the bulk composition: "*Conversely, the non-matrix component in CC chondrites is dominated by Type I chondrules composed of Fe-poor silicates and Fe metal, which contribute minimal oxidized Fe*" (lines 183-184). Moreover, if chondrules did carry some FeO, the matrix mass fractions inferred from our $V_{\mathrm{Fe}}^{\mathrm{nS}}$ proxy would be even lower than reported, further strengthening our conclusion that CC IMPBs accreted matrix-poor material.

2. Sulfur constraints on matrix fractions in CC IMPBs

Lines 120-124: "Sulfur, itself an MVE,..."

The approach using inferred bulk S contents appear to rely heavily on the assumption that S-depletion primarily reflects proto-core segregation, and not volatile loss. This itself is based on the comparison between IVB and IID groups, correct? How well is the impact of S on HSE fractionation constrained? I suggest adding a statement or two here for clarification, given the importance of this step in the modeling.

The reviewer is correct that the IVB-IID comparison is central. We have made the logical chain explicit in the main text and expanded Methods Section 1 with quantitative detail and a worked example (see Overview Point 1 above). The influence of S on HSE partitioning is well-constrained experimentally: partition coefficients for HSEs between solid metal and S-bearing metallic liquid vary by 1-2 orders of magnitude as a function of S content (Chabot et al. 2017; Jones & Drake 1983; Malvin et al. 1986).

Overall comment - Fig. 3.

The data resembles more of a step function than a correlation line. Isn't this more easily explained by extensive volatile (S) loss from IMPBs? Moreover, it should be noted that the data do not preclude CC IMPBs having the same matrix fraction as CO and CV chondrite parent bodies → the error bars are 1SEs, weakening the argument for a systematic increase in matrix fraction over time. I recommend the authors add a paragraph discussing this caveat and alternative explanations than the one they are pushing for.

We have added a paragraph in Section 4.1 discussing these important caveats.

On the step-function appearance: The apparent gap between CC IMPBs (0.08-0.17 matrix) and CO-CV (~0.30) likely reflects incomplete sampling of the accretion time continuum. Primitive achondrites – partially differentiated bodies that accreted within ~1-2.5 Ma after CAIs – bridge this temporal interval, but their matrix fractions have not yet been constrained. We note this as an important direction for future work.

On volatile loss: This possibility is directly addressed by our dual-proxy approach. If S loss explained the low matrix fractions, then the independent Fe valence proxy should not show the same systematic offset – but it does. $V_{\mathrm{Fe}}^{\mathrm{nS}}$ is unaffected by S loss events; it tracks water/oxidant inventories delivered with the matrix. The convergence of two independent proxies rules out volatile loss as an alternative explanation.

On error bars: We agree that uncertainties on individual CC IMPB matrix fractions are substantial, as these are derived quantities with propagated errors. However, the separation is robust in the directly measured parameters themselves: all six CC IMPB groups have lower bulk S contents (0.6-1.1 wt%) than any CC chondrite (1.0-5.3 wt%), and independently, lower $V_{\mathrm{Fe}}^{\mathrm{nS}}$ values (0.7-1.6) than all CC chondrites except CR (Fig. 2). The probability that six independent groups would all fall systematically below chondrite values across two unrelated chemical proxies by chance is vanishingly small. The conversion to matrix mass fractions introduces additional uncertainty, but the underlying chemical distinction is clear in the raw data.

The revised Section 4.1 now includes: "*We note that the data show a compositional gap between CC IMPBs and CO-CV chondrites rather than a smooth continuum. This gap likely reflects incomplete sampling of the accretion time continuum: primitive achondrites, which accreted during the intervening ~1-2.5 Ma interval, are the natural candidates to bridge this gap, but their matrix fractions remain unconstrained – an important target for future work. Despite this gap, the compositional distinction between CC IMPBs and CO-CV chondrites is clear: even accounting for uncertainties, the two populations do not overlap in matrix fraction (Fig. 3), and this separation is independently confirmed by V_{Fe}^{nS} values.*" (lines 257-264)

"This convergence constrains two alternative interpretations. First, low bulk S or low V_{Fe}^{nS} cannot individually reflect temporal evolution of endmember compositions, because S content is governed by nebular condensation chemistry while V_{Fe}^{nS} reflects water-ice delivery and pre-accretionary oxidation of Fe-bearing silicate precursors – independent processes whose simultaneous agreement on low matrix fractions cannot be attributed to time-dependent changes in either parameter alone. Second, low S contents in CC IMPBs cannot reflect secondary volatile loss, because V_{Fe}^{nS} is insensitive to S loss yet shows the same systematic offset between CC IMPBs and chondrites." (lines 231-238)

3. Fe redox constraints on matrix fractions in CC IMPBs

Lines 162-163: "Thus,... matrix abundance."

Here or earlier on, I think the relationship between oxidation state, water-ice abundance, and matrix abundance needs to be explained in more detail. Are the authors arguing that, since water-ice leads to production of secondary mineral phases that add to the matrix, accreted water-ice and accreted matrix are interchangeable, both leading to an increase in Fe valence state? Please clarify.

We are not arguing that water-ice and matrix are interchangeable. Fine-grained matrix is the physical carrier of water-ice (as ice mantles on matrix grains) and of pre-accretionary Fe^{3+}-bearing silicates. More matrix therefore delivers both a larger water-ice inventory (driving parent body aqueous oxidation of $Fe^{2+} \rightarrow Fe^{3+}$) and more pre-accretionary oxidized Fe. Both pathways scale with matrix fraction, establishing the mechanistic link between matrix abundance and Fe valence state. The revised Section 3 described in Overview point 2 explicitly describes these two mechanistic pathways.

Lines 179-180: "By isolating… variable S contents."

Presumably, this is true under the assumption that CC IMPBs were characterized by similarly low redox potential?

The comparison does not require an assumption of similar initial redox potential across CC planetesimals. The redox environment is controlled by the matrix fraction itself: matrix delivers both water-ice (with an approximately constant ice-to-matrix ratio; Alexander 2019) and pre-accretionary oxidized Fe-bearing silicate precursors. The oxidizing capacity acting on the non-sulfide Fe pool therefore scales with matrix fraction. Importantly, the systematic offset between CC IMPBs and chondrites is equally apparent when using *uncorrected* V_{Fe}^{bulk} values (Extended Data Fig. 2), confirming that our conclusion is independent of the sulfide correction.

Lines 188-189: Typo → Fig. 2 has no A and B.

Corrected.

Line 209: In the statement "... Fe oxidation states of the latter," I believe the authors mean "the former" given that the ensuing discussion relates to the CC chondrites.

Corrected. The revised text now reads: "*…CC chondrites would retain their* V_{Fe}^{nS} *values if they had undergone core-mantle differentiation*." (lines 223-224)

Discussion

4.1 Matrix-age correlation from the onset of solar system formation

Lines 240-244: “In a gas-rich disk,... later accretion of matrix-rich planetesimals.”

As mentioned above, it is possible that mm- to cm-scale pebbles are instead dust aggregates that constitute the matrix, in which case the argument for chondrule depletion via size-sorting accompanying planetesimal formation breaks down. Please elaborate.

Addressed comprehensively in our response to Overview Comment 3.

Lines 244-247: “The operation of… planetesimals in extrasolar systems.”

The preferential incorporation of high-Stokes number particles in the streaming instability has never been confined to the Solar System context, but already seen as a general feature of the instability. The comment on extrasolar systems is vague. Please rephrase to add more clarity as to what the authors mean, or remove.

Removed the part on extrasolar systems as suggested by the reviewer. The revised discussion now focuses on the empirical evidence from our solar system.

Lines 255-260: “The matrix-age correlation… heating for core formation.”

Why do NC IMPBs, which accreted around the same time as CC IMPBs, have S-rich cores? Based on earlier work by the leading author (Grewal et al., 2024), redox conditions for both NC and CC IMPBs ought to be similar, suggesting both formed beyond the snowline. Is the implication that NC IMPBs accreted with much more matrix than their CC counterparts?

No. The S-rich cores of NC IMPBs do not require higher matrix fractions. The key difference lies in the S inventories of the non-matrix (chondrule) components in the two reservoirs. In CC chondrites, the non-matrix fraction is severely S-depleted (~0.21 wt% S; this study), so bulk S content is almost entirely controlled by matrix fraction. In ordinary chondrites, which share similar oxidation states with NC IMPBs, the non-matrix component retains substantially more S (~1.4-1.8 wt% S; Alexander 2019). Because NC chondrules are less S-depleted, NC IMPBs could produce S-rich cores even at low matrix fractions. However, as Alexander (2019) emphasized, the matrix-non-matrix mixing story in NC chondrites is considerably more complex, and extending our CC framework to NC IMPBs requires quantitative treatment beyond the scope of this study.

Lines 264-265: “Based on… within the CC reservoir,...”

The CR and IIC parent bodies may have derived from the same local isotopic reservoir, but how does one explain the lack of evolution in the matrix mass fraction within that reservoir over ~2.5

Ma? Doesn't this argue against the argument of chondrule depletion over time? The following statement of "...reflecting accretion from precursor materials distinct… second generation of chondrules" is a regurgitation of words from Hellmann et al. (2023). Here the "distinct precursor materials" is kept vague, but in the following section, the observation that "no alternative population of MVE-depleted, mm-sized aggregates" is known besides chondrules is used to support the claim that chondrules must be the volatile-poor component. Please elaborate.

The reviewer raises an important point about the CR-IIC case. We have substantially revised this discussion in Section 4.1. The persistence of low matrix fractions in the CR-IIC sub-reservoir over ~2.5 Ma does not contradict our framework – rather, it reflects distinct local dynamics within this isotopically defined sub-reservoir. Two mechanisms can account for this: (1) Gurrutxaga et al. (2026) show that during late-stage disk dispersal, photoevaporation separates rigid chondrule-like monomers from fragile matrix dust, producing matrix-poor planetesimals even at late times; and (2) Marrocchi et al. (2022) identified isotopic evidence for two distinct generations of chondrules in CR chondrites, indicating that chondrule-forming events continued within this sub-reservoir, sustaining the local volatile-poor dust supply. In either scenario, wherever volatile-poor material dominated the local solid reservoir, matrix fractions remained low. The CR-IIC case is thus a localized exception consistent with our framework: the matrix-accretion time correlation reflects progressive depletion of volatile-poor material, and where that supply was sustained or replenished by distinct mechanisms, matrix fractions remained low.

The revised text in Section 4.1 now presents both mechanisms rather than relying solely on the sustained chondrule production argument: "*Rather than contradicting the matrix-age correlation, the CR-IIC case likely reflects distinct local dynamics – whether late-stage photoevaporative separation of rigid and fragile dust components*[12] *or a sustained supply of second-generation chondrules*[50]*. In either scenario, wherever volatile-poor material dominated the local solid reservoir, matrix fractions remained low.*" (lines 286-290)

4.2 Early onset of widespread chondrule formation

Lines 281-283: "Second,... size-dependent sorting."

Once again, can one exclude the (likely) possibility that matrix material was held in mm- to cm-scale pebbles?

Addressed comprehensively in our response to Overview Comment 3.

Lines 283-285: "Third,... non-matrix fraction."

This does not strike me as a "line of evidence," but merely a statement amounting to: what else could it be? Please rephrase.

We have also replaced "lines of evidence" with "*observations*" in this section.

Replaced "~~Third, the meteoritic record of CC materials provides no evidence for an alternative population of MVE-depleted, mm-sized aggregates that could constitute a volumetrically significant (83-92% by mass) non-matrix component~~" with "*Third, no other known component in CC materials combines comparable volatile depletion with the volumetric abundance required to constitute 83-92% of accreted mass. The volatile-poor chemistry of the non-matrix fraction in CC IMPBs is consistent with the systematic depletions in MVEs and water characteristic of chondrules formed during high-temperature events*[56,57]." (lines 325-329)

Lines 288-293: "Within this framework,... chondrule-forming epoch."

Are early formed chondrules more prevalent in NC chondrites, and if so, how does that observation fit into this framework?

Early-formed chondrules (ages within the first 1-2 Ma) exist in both NC and CC reservoirs (e.g., Bollard et al. 2017). This observation is consistent with our framework: early chondrule production was widespread across both reservoirs, and early chondrules were preferentially incorporated into rapidly accreting IMPBs where differentiation erased all textural memory. A detailed comparison of chondrule age distributions between NC and CC reservoirs is beyond the scope of the present study.

Lines 308-311: "Independent corroboration… disk evolution."

Please clarify this statement → silicate condensation and chondrule formation are different processes.

The reviewer is correct. These are mechanistically distinct processes. Our intent was not to equate the two but to note that the physical conditions necessary for chondrule formation were available during early disk evolution. We have removed the sentence to avoid ambiguity.

Methods

Lines 602-604: "Because this S depletion… models."

Given the significance of this step in calculating the bulk S content, and for the manuscript to be self-constrained, I recommend the authors provide more detail into how this recovery is accomplished.

Addressed in Overview Point 1. We have expanded Methods Section 1 with: (1) the physical basis for HSE sensitivity to S content, (2) the specific partitioning models and parameterizations used, and (3) a full worked example using the IVB group.

Lines 726-731: "From the core S content, … silicate mantle."

As above, I recommend the authors provide more detail into how this is done, with numbers (perhaps taking one of the CC IMPBs as an example). This will help those interested in validating the calculations for themselves.

Added. *"As a worked example, consider the IVB group. The reconstructed progenitor core contains 8.7 wt% S (see* ***Methods Section 1****). The amount of Fe bound as FeS is calculated stoichiometrically:* Fe_{FeS} *= (55.85/32.07) × 8.7 = 15.2 wt% of the core. The total core Fe content is 72.4 wt%*[28]*, with 18.0 wt% Ni and the remainder as S. Subtracting the sulfide-bound Fe yields a non-sulfide metallic Fe fraction of 57.2 wt% of the core. Combined with a core-to-mantle mass ratio r = 0.075*[28]*,* f_{Fe} *and* f_{ox} *are determined from mass balance.* V_{Fe}^{nS} *is then calculated via the equation above. The resulting* V_{Fe}^{nS} *for IVB is 1.60 (****Extended Data Table 1****). The same procedure is applied to all CC IMPB groups."* (lines 857-864)

Line 791: Add "S" after "wt.%".
Corrected.

Reviewer #2 (Comments for the Author):

Dear Editor,

I have completed my review of the manuscript entitled "Size-dependent sorting governed planetesimal compositions from the onset of solar system formation" by Grewal et al. In this study, the authors present new calculations to estimate the bulk S content of carbonaceous iron meteorite parent bodies, as well as the valence state of Fe excluding sulfide contributions. Based on these approaches, they conclude that IMPBs accreted a larger proportion of non-matrix components, implying that efficient size-dependent sorting operated during the earliest stages of Solar System formation.

Overall, the manuscript is well written, and I appreciate both the motivation and the novelty of the calculations. However, I have identified a conceptual issue, essentially a logical assumption, that should be more carefully addressed before the manuscript can be considered for publication.

The authors estimate the fraction of matrix-like material accreted into IMPBs using Eq. 1. To robustly constrain this relationship, three key parameters must be well defined: (1) the bulk S content of IMPBs, (2) the S content of the matrix component, and (3) the S content of the non-matrix component. While I find the authors' approach to estimating the bulk IMPB S content and the non-matrix endmember generally convincing, I have concerns regarding the use of CI chondrites (corrected for terrestrial contamination) as the matrix endmember.

Specifically, it is unclear whether the matrix phase in late-accreting parent bodies is chemically representative of matrix material present during the earliest stages of Solar System formation. Given that aerodynamic sorting is a pervasive process in the protoplanetary disk, it is reasonable to expect that the composition of residual matrix material evolved over time. If so, the S content of the matrix endmember adopted here may not be applicable to early-accreted bodies such as IMPBs.

We appreciate this concern, which addresses a fundamental assumption of our approach. The most direct counter-argument is compositional: CI chondrite matrix matches the bulk solar system composition for elements other than H, C, N, O, and noble gases. There is no known mechanism by which early matrix would have had a substantially different S content and then returned to solar composition by the time CI chondrites formed ~4 Ma after CAIs. The simplest and most parsimonious interpretation is that the S content of CI-like matrix was approximately solar throughout the disk lifetime, as expected for a component whose volatile element budget is set by nebular condensation chemistry rather than thermal processing.

Three additional observations support this conclusion. First, S in CI-like matrix is hosted in nm- to µm-scale troilite grains physically embedded within the matrix aggregate. Aerodynamic sorting separates particles by size but does not fractionate the internal chemical composition of fine-grained matrix. Second, the S-matrix correlation in CC chondrites is linear across groups spanning ~2 Ma of accretion time (Fig. 1A), with no systematic residual trend between early-accreting (CO, CV) and late-accreting (CM, CI) groups. If matrix S content evolved substantially, deviations from linearity would be expected but are not observed. Third, the independent Fe valence proxy, which is insensitive to matrix S content and governed by entirely different physics (water-ice delivery and silicate oxidation), shows the same systematic offset between CC IMPBs and chondrites, confirming that the signal reflects genuinely low matrix fractions rather than temporal evolution of matrix composition.

We have added a paragraph at the end of Methods Section 2 addressing the temporal stability of the matrix S endmember: *"The use of CI chondrites as the matrix endmember assumes that the S content of CI-like matrix was approximately constant throughout the lifetime of the CC reservoir. CI chondrite matrix represents the unfractionated bulk solar system composition for elements other than H, C, N, O, and noble gases, and there is no known mechanism by which early matrix would have had a substantially different composition and subsequently returned to solar values by the time CI chondrites formed. Aerodynamic sorting separates particles by size but does not fractionate the chemical composition of fine-grained matrix, because S-bearing phases (nm- to µm-scale troilite grains) are physically embedded within the matrix and transported with it. Empirically, this assumption is supported by the linearity of the S-matrix mass fraction regression across CC chondrites spanning ~2 Ma of accretion history (**Fig. 1A**), with no systematic residual trend between early-accreting (CO, CV) and late-accreting (CM, CI) groups. The independent Fe valence proxy (**Section 3**), which is insensitive to matrix S content and instead tracks water-ice delivery, confirms the same systematic offset between CC IMPBs and chondrites, providing independent validation of this assumption."* (lines 717-729)

More broadly, sorting in the early Solar System was likely coupled with continuous recycling of dust. Considering that the total dust mass in the disk was substantially larger than that ultimately incorporated into chondrite parent bodies, it is plausible that such processes could have progressively modified the chemical composition of the residual matrix. For example, S could have become enriched in the remaining fine-grained component as dust mass decreased. Under such a scenario, the authors' conclusion that IMPBs accreted volatile-poor material may still hold, but it would not necessarily require a higher proportion of non-matrix components; instead, it could reflect temporal evolution in matrix composition.

The reviewer's suggestion that dust recycling could have progressively enriched S in residual matrix is a specific instance of the temporal evolution scenario addressed above. Two additional considerations argue against this. First, the total dust mass in the protoplanetary disk was substantially larger than that ultimately incorporated into planetesimals. If thermally processed material represented only a small fraction of the total dust budget, mass balance requires that its removal would not significantly alter the composition of the remaining fine-grained reservoir. Second, as noted above, CI chondrite matrix matches the bulk solar system composition for elements other than H, C, N, O, and noble gases. If early matrix had been S-poor and progressively enriched through recycling, it would need to arrive precisely at solar composition by the time CI chondrites formed – a coincidence for which there is no physical basis. The simplest interpretation is that matrix composition remained approximately solar throughout the disk lifetime. Empirically, the linearity of the S-matrix correlation across CC chondrites spanning ~2 Ma shows no evidence for progressive enrichment, and the independent Fe valence proxy confirms low matrix fractions regardless of any assumed evolution in matrix S content.

This concern also extends to the Fe valence proxy. The authors' interpretation relies on the implicit assumption that matrix components in both early- and late-accreting parent bodies contained comparable amounts of water (ice) and underwent similar degrees of aqueous alteration. However, this assumption may not be valid. Early accreting parent bodies likely experienced shorter timescales before differentiation, collision, or growth into larger bodies, potentially limiting the duration and extent of aqueous alteration. As a result, Fe valence may be, at least in part, a time-dependent parameter rather than solely a function of matrix abundance.

The reviewer raises two related concerns: (1) whether early matrix contained comparable amounts of water-ice, and (2) whether early-accreting bodies had sufficient time for aqueous alteration.

On water-ice content: The ice-to-matrix ratio in CC chondrites is approximately constant across groups (Alexander 2019), because water-ice condensation beyond the snowline is governed by local temperature rather than the timing of planetesimal accretion. There is no known mechanism to systematically change the ice-to-dust ratio over the ~3 Ma timescale of CC planetesimal formation.

On alteration timescales: We have added a new Methods Section 6 that addresses this quantitatively. Two key points:

First, $V_{\mathrm{Fe}}^{\mathrm{nS}}$ does not solely reflect aqueous alteration – it also records the oxidation state of pre-accretionary Fe-bearing amorphous silicate precursors in the matrix (refs. 44–46), which were already oxidized prior to accretion. Low matrix fractions therefore produce low $V_{\mathrm{Fe}}^{\mathrm{nS}}$ independent of the extent of parent body processing.

Second, experimental and modeling studies demonstrate that aqueous alteration reactions proceed rapidly, completing on timescales of 10^2-10^3 years at temperatures of 273-473 K, orders of magnitude shorter than the ~10^5-10^6 years required for ^{26}Al heating to reach metal-silicate separation temperatures (>1260 K). Aqueous alteration necessarily precedes and completes before core formation.

The revised Methods Section 6 now includes:

*"6. "**Timing of aqueous alteration relative to differentiation***

A separate concern is whether early-accreting CC IMPBs experienced sufficient aqueous alteration before differentiation to establish meaningful V_{Fe}^{nS} values. Experimental and modeling studies demonstrate that aqueous alteration reactions proceed rapidly, completing on timescales of 10^2-10^3 years at temperatures of 273-473 K[79], orders of magnitude shorter than the ~10^5-10^6 years required for ^{26}Al heating to reach metal-silicate separation temperatures (>1260 K)[80]. Since both processes are driven by the same ^{26}Al heat source and temperatures must pass through the aqueous alteration window before reaching the differentiation threshold, aqueous alteration necessarily precedes and completes before core formation. Furthermore, V_{Fe}^{nS} does not solely reflect post-accretionary aqueous alteration. It also records the oxidation state of pre-accretionary Fe-bearing amorphous silicate precursors in the matrix[43–45], which were already partially oxidized prior to accretion. Low matrix fractions therefore produce low V_{Fe}^{nS} independent of the extent of parent body processing, because less matrix delivers less oxidizing agent and oxidized precursor regardless of whether aqueous alteration ran to completion."
(lines 928-941)

In summary, the manuscript would benefit from a more thorough assessment of whether matrix-like components remained chemically consistent through time. Without adequately justifying this assumption, the interpretation linking S content and Fe valence directly to matrix fraction-and, by extension, to early sorting processes-remains uncertain.

We believe the responses above, together with the revisions to Methods Sections 2 and 6 and the addition at the end of Section 3, provide the thorough assessment the reviewer requests.

In addition we have added at the end of Section 3: "*This convergence excludes two alternative interpretations. First, low bulk S or low* V_{Fe}^{nS} *cannot individually reflect temporal evolution of endmember compositions, because S content is governed by nebular condensation chemistry while* V_{Fe}^{nS} *reflects water-ice delivery and pre-accretionary oxidation of Fe-bearing silicate precursors – independent processes whose simultaneous agreement on low matrix fractions cannot be attributed to time-dependent changes in either parameter alone. Second, low S contents in CC IMPBs cannot reflect secondary volatile loss, because* V_{Fe}^{nS} *is insensitive to S loss yet shows the same systematic offset between CC IMPBs and chondrites.*" (lines 231-238)

Minor comments:

Line 129: The variables in Eq. 1 should be clearly defined in the text.

Done. Added *"where* f_M *is the matrix mass fraction,* C_S^{bulk} *is the bulk IMPB S content, and* C_S^{NM} *and* C_S^{M} *are the S content of the non-matrix and matrix endmembers, respectively."* (lines 142-143)

Line 604: More detail should be provided on how bulk S contents of IMPBs are estimated using HSE-based models.

Addressed together with Reviewer 1's comment on Lines 602–604. We have expanded Methods Section 1 with the physical basis for HSE sensitivity to S content, the specific partitioning models used, and a worked example using the IVB group (see Overview Point 1).

Line 615: The sensitivity of Cbulk to variations in the parameter r should be discussed.

Added in Methods Section 1: "*The sensitivity of* C_S^{bulk} *to r is given by* $\partial C_S^{bulk}/\partial r = C_S^{core}/(1+r)^2$, *which shows that* C_S^{bulk} *scales approximately linearly with r at the low core mass fractions applicable to all CC IMPBs (r = 0.075-0.205). In practice, the uncertainty in* C_S^{bulk} *is dominated by the uncertainty in* C_S^{core} *(typically 2-3 wt% from fractional crystallization models) rather than* *r, which is constrained to within ±0.01. The propagated 1σ uncertainties are reported in* ***Extended Data Table 1."*** (lines 694-699)

Reviewer #1 (Comments for the Author):

Nature Astronomy: Response to revised manuscript from Grewal et al. titled Aerodynamic sorting governed planetesimal compositions from the onset of solar system formation (NATASTRON-26020234)

Overall Reception

The authors have addressed most of my concerns to a satisfactory degree. I particularly appreciate their clarification of the logic underlying the calculation and use of IMPB bulk S contents, as well as the relationship between matrix abundance and Fe oxidation state. Below, I provide several final concerns/suggestions intended to strengthen the manuscript for publication.

We thank Reviewer #1 for the positive assessment and useful set of suggestions.

General Comments

Dynamic argument: Differential delivery + fragmentation rates
Regarding differential delivery rates, it is important to clarify that for a given particle size, denser particles such as chondrules drift inwards faster than low-density aggregates of matrix grains. I agree with the authors that mm-sized chondrules would drift faster than matrix monomers, but again, the transport of matrix material is not controlled by monomer size → pebbles composed of matrix can be cm-scale, exceeding the size of chondrules and drifting inwards faster despite the density contrast. The second mechanism, that of differential fragmentation in pressure bumps, seems more robust.

We agree with the reviewer. The radial transport of matrix is not set by monomer size, and matrix can coagulate into cm-scale aggregates whose Stokes numbers and drift rates rival or exceed those of mm-sized chondrules. We have revised the Introduction and Section 4.1 to foreground the differential fragmentation and filtering mechanism (Gurrutxaga et al. 2026), in which mechanically rigid chondrules are preferentially retained while fragile, porous matrix aggregates are disrupted, as the more robust pathway, and we now state the reviewer's caveat explicitly where the Stokes-number contrast is mentioned. We emphasize that our central conclusion is chemical: the systematic matrix depletion of CC IMPBs is established by the S and Fe-valence proxies independently of which dynamical mechanism dominates.

Replaced "~~This fractionation can arise from primarily from contrasts in Stokes number, which scales with the product of internal particle density and size, and from the differential response of mechanically rigid and fragile dust components to collisional fragmentation and aerodynamic filtering~~." with "This fractionation can arise from primarily from the differential response of mechanically rigid and fragile dust components to collisional fragmentation and aerodynamic filtering, which preferentially retains compact, chondrule-rich material while disrupting porous matrix aggregates. Contrasts in Stokes number, set by the product of particle density and size, may also contribute, though because matrix can coagulate into large aggregates, size and density alone need not favor chondrule-rich material." (lines 47-52)

~~"This fractionation can arise from contrasts in aerodynamic behavior between compact, volatile-poor and porous, volatile-rich dust components, whether through Stokes number-governed differential concentration or differential fragmentation and filtering in disk substructures."~~ with "This fractionation arises principally from the differential fragmentation and filtering of rigid and fragile dust components in disk substructures, which preferentially retains compact, volatile-poor material, while Stokes number-governed concentration may also contribute, although matrix can coagulate into large aggregates whose aerodynamic behavior need not differ from that of chondrules" (lines 264-268)

Additionally, is it assumed that CC IMPBs accreted in a pressure bump, as is believed for CC chondrite parent bodies? The authors should clarify if this is the envisioned scenario. If so, is there a correlation between the matrix fraction of IMPBs and their nucleosynthetic isotopic composition – reflecting an evolution in dust heritage at the pressure bump? Please elaborate.

Yes, the envisioned scenario is that CC planetesimals, from the earliest IMPBs through the later chondrite parent bodies, accreted within the same long-lived pressure bump that concentrated CC solids, as modeled by Gurrutxaga et al. (2026). The progressive increase in matrix fraction with accretion time then reflects the temporal evolution of aerodynamic sorting within this structure. We have added a sentence to Section 4.1 stating this explicitly.

"In the scenario we envision, CC planetesimals from the earliest IMPBs through the later chondrite parent bodies accreted within the same long-lived pressure bump that concentrated CC solids, with the increase in matrix fraction over time reflecting the progressive evolution of aerodynamic sorting within this structure." (lines 273-276)

Regarding a possible correlation between IMPB matrix fraction and nucleosynthetic composition: this is an insightful question, and an evolving dust heritage at the bump could in principle imprint such a correlation. The clearest isotopic structure currently resolvable is between sub-reservoirs rather than along a single matrix-fraction sequence: the low-matrix CR chondrites and IIC IMPB, for example, are offset in Fe-Ni isotopes from the main CC trend and are inferred to have formed in a distinct, long-lived sub-reservoir (Section 4.1). A finer, systematic matrix-isotope correlation cannot be tested at present, because the nucleosynthetic data for CC IMPBs (Δ95Mo, ε62Ni) carry uncertainties large enough that ref.6 explicitly cautioned against precise matrix-fraction estimates from them. We note this as a promising direction for future work once higher-precision isotopic data become available, rather than over-interpreting the current dataset.

Argument regarding higher S contents in NC chondrules.

The authors argue in their response that NC chondrules are less S-depleted and could thus produce S-rich cores even at low matrix fractions. This should be included in the main text.

Done. Added "The S-rich NC cores, by contrast, arise because NC non-matrix material is far more S-rich: in matrix-poor ordinary chondrites, which match NC IMPBs in redox state28, the chondrule component is estimated to contain ~1.4-1.8 wt%53, far higher than the CC non-matrix endmember (~0.21 wt%)." (lines 301-304)

Specific Comments

Lines 20 & 102: relationship between Fe oxidation/valence state and water-ice content
As the authors have noted, the Fe valence state reflects both the incorporation of water-ice and pre-accretionary oxidized precursors, both falling under the umbrella of matrix material. I suggest modifying these two lines to reflect the contribution of the latter.

We have modified both lines so that Fe valence is described as integrating two matrix-hosted contributions, water-ice delivery and pre-accretionary oxidized Fe-bearing silicate precursors, both scaling with matrix abundance. (lines 20-21 and 103-105)

Line 56: "... gas surface densities were at their highest…"
What is the significance of high gas surface densities here? Would remove if unjustified.

We have removed this clause. The high early gas surface density was not essential to our argument and, as the reviewer notes, its relevance was not established.

Lines 258-261: "The gap probably… future work."
What is the source for the claim that the achondrite parent bodies accreted during the intervening ~1 to 2.5Ma interval? Presumably some achondrites represent the mantles of the IMPBs considered here.

We thank the reviewer for raising this point. We have removed the paragraph discussing primitive achondrites as candidates to bridge the compositional gap between CC IMPBs and CO-CV chondrites. As the reviewer notes, some primitive achondrites likely represent the silicate mantles of the IMPBs considered here, in which case they accreted during the same early epoch rather than during a later intervening interval, and the accretion timing we had implied is not robustly constrained. We agree the original framing was speculative and have removed it. The compositional distinction between CC IMPBs and CO-CV chondrites remains clearly established in the preceding text and in Fig. 3.

Line 286: "... the CR-IIC case likely reflects…"
I suggests softening the language to "possibly reflects" or "may reflect."

We have softened "likely reflects" to "may reflect" as suggested.

Line 289: “... wherever volatile-poor… local solid reservoir”
I would remove this phrase, and modify the sentence slightly to: “In either scenario, matrix fractions could remain low.”

We have adopted the reviewer’s suggested wording.

Reviewer #2 (Comments for the Author):
The authors have successfully addressed all of my concerns and those of the other reviewer. The paper is now well-polished, and I am happy to recommend its acceptance for publication.

We thank Reviewer #2 for the positive assessment and recommendation for acceptance.

Nature Astronomy: **Review of manuscript from Grewal et al. titled *Size-dependent sorting governed planetesimal compositions from the onset of solar system formation* (NATASTRON-26020234)**

Overview

This paper presents a novel approach to constrain the matrix fractions of carbonaceous iron meteorite parent bodies (CC IMPBs), with the goal of assessing if the positive correlation between matrix abundance and accretion age inferred for CC chondrite parent bodies extends to the first ~2 Myr of Solar System history, during which the IMPBs formed. The approach relies on the bulk S content and Fe valence states of the IMPBs, inferred via the S concentration and Fe/Ni ratio of their cores (*i.e.,* iron meteorites), respectively, and mass balance. The key finding is that CC IMPBs were matrix-poor, characterized by matrix fractions < 20%, substantially lower than those of CC chondrites. Based on this result, the authors argue that forming CC planetesimals were increasingly matrix-rich across the lifetime of the CC reservoir, not only in its later stages (> 2 Myr following CAIs, when chondrites accreted). The authors further identify the volatile-poor component constituting the bulk of CC IMPBs with mm-scale chondrules, leading to their conclusion that (i) chondrule formation was widespread and early, preceding IMPB formation, and (ii) preferential incorporation of chondrules in planetesimal formation led to the progressive depletion of chondrules in the CC reservoir over time.

Overall Reception

The work constitutes an **original step towards a first-order understanding of first-generation planetesimal compositions, a subject which holds significant bearing on models of early Solar System evolution, and therefore of great scientific interest.** The manuscript is overall well written, and the approach taken emphasizes the utility of chemical proxies in a field which discourse has, in recent years, been largely centered on nucleosynthetic isotope anomalies. **While the main idea of the approach is simple, its execution is founded on a plethora of assumptions that warrant scrutiny and deserve either more explicit mention, or detailed explanation.** On the chemistry front, for instance, the string of logic underlying the calculation of IMPB bulk S contents appears to rest heavily on an inference drawn from comparing the MVE signatures of IVB and IID meteorites. This should be more explicitly stated in the main text, and described more quantitatively in the supplementary. Also, the connection between Fe valence state, water-ice abundance, and matrix abundance is vague. On the dynamical front, it is unclear whether mm-scale chondrules were the largest particles present in planetesimal formation. Pebbles consisting of matrix material can conceivably grow to the cm-scale, as typically envisioned in dust coagulation models – pebbles are often described as "fluffy" dust aggregates. The prevalence of chondrules in the Solar System has also been called into question, reflecting as it may a sampling bias in our meteorite collections. These caveats should be discussed, in the supplementary if not the main text. Contents of the supplementary, while clear, call for additional detail/elaboration that will serve to inspire confidence in the methodology.

To summarize, **owing to the far-reaching implications of the work presented, along with its novelty, the manuscript merits publication after revision.** Below are my specific comments, which address the points raised above among others, and which I hope will contribute to a stronger manuscript.

Specific Comments - Main Text

1. Introduction

Line 33-34: "Chondrules and refractory inclusion abundances decline systematically with increasing matrix fraction."

This appears obvious – aside from chondrules, CAIs, and AOAs, what else is there (aside from small Fe metal grains, etc.) but matrix? Would remove.

Line 34: "...matrix mass fraction in CC chondrites increases"

The authors state this plainly, indicating the matrix-accretion age correlation is well-established and robust. The uncertainties in accretion ages from Hellmann et al. (2023) are so large that those of CI, CM, CR, and Tagish Lake parent bodies are indistinguishable. Moreover, those of CO and CV are indistinguishable as well. I suggest using softer language.

Line 44-45: "...to accrete into planetesimals before very fine-grained (nm-scale) matrix dust".

In models of dust coagulation in protoplanetary disks, dust particles are often envisioned as mm- to cm-sized aggregates that (i) themselves consists of fine-grained particles (micron-scale), and (ii) limited in growth by fragmentation or radial drift (*e.g.,* Birnstiel et al., 2012). Thus, is it not possible that matrix is held in pebbles with characteristic sizes similar to, or exceeding, mm-scale chondrules? While they are made of smaller grains, the dynamics of such pebbles (*i.e.,* incorporation into planetesimals during hydrodynamic instabilities), is governed by their characteristic size. In this case, the size-sorting argument is severely weakened. Please elaborate.

Line 48: "...gas-rich disk… already forming."

What is meant by "dynamically active" - the disk evolves across its entire lifetime. Please clarify. Also, please clarify what the authors mean by "gas-solid coupling… [was] most efficient."

Line 95: "...as water is the principal oxidant in CC planetesimals."

The link between oxidation state and water abundance warrants caution. Condensation in the presence of dust enrichment can yield oxidized condensates (*e.g.,* Ebel & Grossman, 2000). The authors later discuss how dust enrichment in pressure maxima facilitate both chondrule and planetesimal formation.

2. Sulfur constraints on matrix fractions in CC IMPBs

Lines 120-124: "Sulfur, itself an MVE,..."

The approach using inferred bulk S contents appear to rely heavily on the assumption that S-depletion primarily reflects proto-core segregation, and not volatile loss. This itself is based on the comparison between IVB and IID groups, correct? How well is the impact of S on HSE fractionation constrained? I suggest adding a statement or two here for clarification, given the importance of this step in the modeling.

Overall comment - Fig. 3.

The data resembles more of a step function than a correlation line. Isn't this more easily explained by extensive volatile (S) loss from IMPBs? Moreover, it should be noted that the data do not preclude CC IMPBs having the same matrix fraction as CO and CV chondrite parent bodies → the error bars are 1SEs, weakening the argument for a systematic increase in matrix fraction over time. I recommend the authors add a paragraph discussing this caveat and alternative explanations than the one they are pushing for.

3. Fe redox constraints on matrix fractions in CC IMPBs

Lines 162-163: "Thus,... matrix abundance."

Here or earlier on, I think the relationship between oxidation state, water-ice abundance, and matrix abundance needs to be explained in more detail. Are the authors arguing that, since water-ice leads to production of secondary mineral phases that add to the matrix, accreted water-ice and accreted matrix are interchangeable, both leading to an increase in Fe valence state? Please clarify.

Lines 179-180: "By isolating… variable S contents."

Presumably, this is true under the assumption that CC IMPBs were characterized by similarly low redox potential?

Lines 188-189: Typo → Fig. 2 has no A and B.

Line 209: In the statement "... Fe oxidation states of the latter," I believe the authors mean "the former" given that the ensuing discussion relates to the CC chondrites.

Discussion

4.1 Matrix-age correlation from the onset of solar system formation

Lines 240-244: "In a gas-rich disk,... later accretion of matrix-rich planetesimals."

As mentioned above, it is possible that mm- to cm-scale pebbles are instead dust aggregates that constitute the matrix, in which case the argument for chondrule depletion via size-sorting accompanying planetesimal formation breaks down. Please elaborate.

Lines 244-247: "The operation of… planetesimals in extrasolar systems."

The preferential incorporation of high-Stokes number particles in the streaming instability has never been confined to the Solar System context, but already seen as a general feature of the instability. The comment on extrasolar systems is vague. Please rephrase to add more clarity as to what the authors mean, or remove.

Lines 255-260: "The matrix-age correlation… heating for core formation."

Why do NC IMPBs, which accreted around the same time as CC IMPBs, have S-rich cores? Based on earlier work by the leading author (Grewal et al., 2024), redox conditions for both NC and CC IMPBs ought to be similar, suggesting both formed beyond the snowline. Is the implication that NC IMPBs accreted with much more matrix than their CC counterparts?

Lines 264-265: "Based on… within the CC reservoir,..."

The CR and IIC parent bodies may have derived from the same local isotopic reservoir, but how does one explain the lack of evolution in the matrix mass fraction within that reservoir over ~2.5 Ma? Doesn't this argue against the argument of chondrule depletion over time? The following statement of "...reflecting accretion from precursor materials distinct… second generation of chondrules" is a regurgitation of words from Hellmann et al. (2023). Here the "distinct precursor materials" is kept vague, but in the following section, the observation that "no alternative population of MVE-depleted, mm-sized aggregates" is known besides chondrules is used to support the claim that chondrules must be the volatile-poor component. Please elaborate.

4.2 Early onset of widespread chondrule formation

Lines 281-283: "Second,... size-dependent sorting."

Once again, can one exclude the (likely) possibility that matrix material was held in mm- to cm-scale pebbles?

Lines 283-285: "Third,... non-matrix fraction."

This does not strike me as a "line of evidence," but merely a statement amounting to: what else could it be? Please rephrase.

Lines 288-293: "Within this framework,... chondrule-forming epoch."

Are early formed chondrules more prevalent in NC chondrites, and if so, how does that observation fit into this framework?

Lines 308-311: "Independent corroboration… disk evolution."

Please clarify this statement → silicate condensation and chondrule formation are different processes.

Methods

Lines 602-604: "Because this S depletion… models."

Given the significance of this step in calculating the bulk S content, and for the manuscript to be self-constained, I recommend the authors provide more detail into how this recovery is accomplished.

Lines 726-731: “From the core S content, … silicate mantle.”

As above, I recommend the authors provide more detail into how this is done, with numbers (perhaps taking one of the CC IMPBs as an example). This will help those interested in validating the calculations for themselves.

Line 791: Add “S” after “wt.%”.