ISOTOPIC COMPLEMENTARITY OF CHONDRULES AND MATRIX AND THE AGE AND ORIGIN OF CHONDRULES. G. Budde, T. Kleine, T. S. Kruijer, C. Burkhardt, and K. Metzler; Institut für Planetologie, University of Münster, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany; gerrit.budde@uni-muenster.de.

Introduction: Chondrules are a major constituent of primitive meteorites, but their origin remains enigmatic. Two fundamentally different classes of formation models have been proposed. In the first set of models, chondrules formed by melting of dust aggregates in the solar nebula [e.g., 1], while in the second class of models they are the product of collisions between protoplanetary bodies [2-4]. Chondrules are embedded in a fine-grained matrix, and in carbonaceous chondrites these two components are chemically complementary. This complementarity has been used to argue for a common origin of both chondrules and matrix from a single reservoir of solar nebular dust [5], but the significance of this chemical complementarity and whether it can distinguish between an impact and nebula origin of chondrules is debated.

A further complicating factor for constraining the origin of chondrules is that their chronology is not well understood. Pb-Pb ages for individual chondrules suggest that chondrule formation began contemporaneously with CAI formation and continued for >3 Ma [6]. However, such a prolonged interval of chondrule formation is difficult to reconcile with the distinct physical and chemical properties of chondrules from a given chondrite group, which imply formation in a narrow time interval [e.g., 1]. Moreover, Al-Mg ages for individual chondrules typically provide ages of ~2 Ma after CAI formation, indicating that the majority of chondrules formed in a short time interval [e.g., 7].

Here we address these issues using high-precision W isotope measurements on chondrules and matrix separated from the Allende CV3 chondrite. Tungsten isotope variations may arise (i) through the decay of short-lived $^{182}$Hf to $^{182}$W (half-life = 8.9 Ma), resulting in radiogenic $^{182}$W variations, and (ii) through the heterogeneous distribution of the distinct products from the slow ($s$-process) and rapid ($r$-process) neutron capture processes, resulting in nucleosynthetic W isotope anomalies. Thus, W isotopes cannot only be used to date chondrules, but also to assess potential genetic links between chondrules and matrix.

Methods: We have analyzed three matrix and six chondrule fractions (155 to ~3000 chondrule fragments and intact chondrules each), as well as two bulk powders of Allende. Matrix and chondrule fractions were prepared either by freeze-thaw disaggregation or by sieving and hand-picking from a gradually crushed ~40 g slice of Allende. All chondrule fractions were carefully purified by hand-picking and sonication in acetone. Samples were digested in Savillex beakers using HF-HNO$_3$(HClO$_4$), followed by inverse aqua regia. Hf and W concentrations were determined by isotope dilution on small aliquots of the sample solutions, and W was separated from the sample matrix following our established procedures [8].

The W isotope compositions were measured on a Neptune Plus MC-ICP-MS at Münster [8]. The W isotope data are normalized to either $^{186}$W/$^{183}$W (‘6/3’) or $^{186}$W/$^{184}$W (‘6/4’) and reported as $\varepsilon$-unit deviations (i.e., 0.01%) relative to the bracketing standards. The precision and accuracy of the W isotope analyses were assessed by repeated measurements of the BHVO-2 rock standard, which was processed together with each set of samples, and yielded mean $\varepsilon^{183}$W (6/4) = –0.02 ± 0.09 and $\varepsilon^{182}$W (6/3) = –0.03 ± 0.12 (2 s.d., n=29) for ~30 ng W consumed per analysis.

Results: The chondrule and matrix fractions display large and complementary variations in $\varepsilon^{183}$W (i.e., $^{183}$W/$^{184}$W), while bulk Allende shows no or only small $^{183}$W anomalies (Fig. 1). Because variations in $^{183}$W can only be nucleosynthetic in origin, they indicate that the matrix is enriched in $s$-process (or depleted in $r$-process) W isotopes, while chondrules exhibit a complementary $s$-deficit (or $r$-excess). We also obtained preliminary Mo isotope data for the same samples.
analyzed for W isotopes; the Mo data show characteristic s-deficit and -excess patterns and indicate that s-process material is enriched in matrix over chondrules.

The chondrules and matrix samples also show complementary anomalies in \( \varepsilon^{182}W \). These are correlated with Hf/W and, after correction for nucleosynthetic W isotope anomalies after [8], chondrules and matrix define an isochron that corresponds to an age of 2.2 ± 0.8 Ma after CAI formation (Fig. 2). This age is in good agreement with most Al-Mg ages for chondrules from carbonaceous and ordinary chondrules [7].

![Fig. 2. Hf-W isochron for Allende matrix and chondrules. Also shown is the bulk CAI isochron (dashed line) from [8].](image)

**Origin of chondrules:** The isotopic complementarity of chondrules and matrix cannot reflect parent body processes or incomplete dissolution of presolar phases, but was most likely established during chondrule formation. As such, the W isotopic data provide critical insights into possible chondrule formation mechanisms. First, these data rule out formation of chondrules by protoplanetary collisions. Because bulk meteorites and inner solar system planets show only small if any \( \varepsilon^{183}W \) anomalies (Fig. 1), any two planetary bodies that would have collided to produce chondrules also had no significant \( \varepsilon^{183}W \) anomaly. Consequently, chondrules could not have formed from 'splashes' of melt produced by the collision of molten bodies [3] and also not by jetting during impacts on undifferentiated bodies [2]. The isotopic data are also inconsistent with the X-wind or similar models, in which chondrules and matrix formed independently from each other in the solar nebula. These models cannot explain why chondrules and matrix have isotope anomalies that correspond to the enrichment and a complementary depletion of a single presolar carrier. Moreover, there is no reason why random mixing of chondrules and matrix with large and complementary \( \varepsilon^{183}W \) anomalies should result in the bulk inner solar system \( \varepsilon^{182}W \) of \( -0 \).

Models in which chondrules formed through melting of dust, either by shock waves [9] or current sheets [10], are fully consistent with the isotopic data. In these models, matrix represents the dust that did not melt; chondrules and matrix (from a given chondrite group), therefore, derive from a common reservoir of nebular dust. Because bulk meteorites and terrestrial planets are nearly homogeneous for \( ^{182}W \), such a reservoir of nebular dust would have been characterized by \( \varepsilon^{183}W \approx 0 \). The preferential incorporation of an s-process carrier (e.g., SiC) into matrix—perhaps as a result of sorting of dust grains according to their size or type—can then readily account for the complementary nucleosynthetic isotope anomalies observed for chondrules and matrix.

**Timing of chondrule formation:** After their formation, no (or only very minor) amounts of matrix or chondrules were lost, because otherwise the bulk chondrite would show a significant \( \varepsilon^{183}W \) anomaly. To prevent this loss in a turbulent solar nebula, where small particles like chondrules would rapidly mix and homogenize [1], this requires that chondrules and matrix accreted rapidly to a chondrite parent body. Thus, chondrules from a given chondrite should be characterized by very similar formation ages. Hence, the Hf-W systematics of Allende chondrules and matrix indicate that the vast majority of Allende chondrules formed at ~2.2 Ma after CAI and within a narrow time interval of less than ±0.6 Ma (i.e., the uncertainty deriving solely from the scatter on the isochron). This is consistent with Al-Mg ages for most chondrules, but is more difficult to reconcile with the range of Pb-Pb ages from ~0 to ~3 Ma after CAI formation that has been reported for Allende chondrules [6]. However, such a prolonged interval of chondrule formation is inconsistent with the need for rapid accretion of chondrules and matrix to preserve the inner solar system \( \varepsilon^{183}W \) of bulk chondrites.

**References:**