

CHONDRITE DIVERSITY REVEALED BY CHROMIUM, CALCIUM AND MAGNESIUM ISOTOPES.

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Introduction: Ungrouped chondrites significantly contribute to the chondrite diversity [e.g., 1, 2], but their origin remains poorly understood. Different chondrites record large chemical and isotopic variations amongst them [3, 4], which reflect their origins and accretion conditions. In this study, we report the high-precision mass-independent isotope data for a variety of chondrites (ungrouped, Kakangari and enstatite-rich) as: $\epsilon^{53}\text{Cr}$ (radiogenic; $\sim 3\text{ppm}$), $\epsilon^{54}\text{Cr}$ (nucleosynthetic; $\sim 6\text{ppm}$), $\epsilon^{48}\text{Ca}$ (nucleosynthetic; $\sim 17\text{ppm}$) and $\mu^{26}\text{Mg}^*$ (radiogenic; $\sim 3\text{ppm}$). All the data are produced by MC-ICP-MS, and the related analytical methods as used as [5] for Cr, [6] for Ca and [7] for Mg isotope measurements. We mainly discussed the following issues: **1)** $\epsilon^{54}\text{Cr}$ and $\epsilon^{48}\text{Ca}$ values of enstatite and Kakangari chondrites; **2)** Itqiy parent body [8] observed by $\epsilon^{48}\text{Ca}$ systematics; **3)** using ungrouped chondrites to test the isotope dichotomy of the Solar System; **4)** searching for potential relationships between ungrouped chondrites based on $\epsilon^{54}\text{Cr}$ and $\epsilon^{48}\text{Ca}$ data; **5)** carrying phases of ^{54}Cr , ^{50}Ti and ^{48}Ca anomalies; **6)** lack of ^{26}Al - ^{26}Mg bulk isochron for chondrites.

Results and Discussion: SAH 97096 (EH3) possesses a $\epsilon^{48}\text{Ca}$ value of -0.19 ± 0.22 . The $\epsilon^{48}\text{Ca}$ value for SAH 97096 is -0.19 ± 0.22 , which is consistent with previous data from [9] (-0.27 ± 0.14 , $N=2$). SAH 97096 has the same $\epsilon^{48}\text{Ca}$ value as that of Earth (0.00 ± 0.11 , 2SD) and Moon (0.04 ± 0.04 , 2SD) [6, 10]. LEW 87232 (K3) has $\epsilon^{54}\text{Cr}$ and $\epsilon^{48}\text{Ca}$ values of -0.44 ± 0.04 and -1.30 ± 0.25 , respectively. Although it shares similar $\epsilon^{54}\text{Cr}$ values with ordinary chondrites (OCs; -0.39 ± 0.10), but their different $\epsilon^{48}\text{Ca}$ and $\Delta^{17}\text{O}$ compositions exclude a common origin.

Itqiy (EH7) and two enstatite-rich clasts, MS-MU-19 and MS-MU-36, show homogenous $\epsilon^{48}\text{Ca}$ values, averaging at -0.35 ± 0.10 (2SD). This value is clearly lower than that Earth-Moon system and slightly lower than that of the EC, combined with their $\epsilon^{54}\text{Cr}$ (-0.26 ± 0.03 , 2SD, $N=2$) and $\epsilon^{50}\text{Ti}$ (-0.34 ± 0.03 , 2SD; two replicate measurements for Itqiy) data [8, 11], suggesting different origins for Itqiy parent body and ECs and Earth-Moon system.

Based on our data (**Figure 1**), all the ungrouped CCs have $\epsilon^{54}\text{Cr}$ values > 0.3 , while the three ungrouped NCs and also one K chondrite (belongs to NC) possess $\epsilon^{54}\text{Cr}$

values lower than 0.3. All the three ungrouped NCs and one K chondrite possess negative $\epsilon^{48}\text{Ca}$ values (at most -0.4), while all the ungrouped CCs have positive $\epsilon^{48}\text{Ca}$ values (> 0.28). Both $\epsilon^{54}\text{Cr}$ and $\epsilon^{48}\text{Ca}$ systematics confirmed the CC-NC isotopic dichotomy.

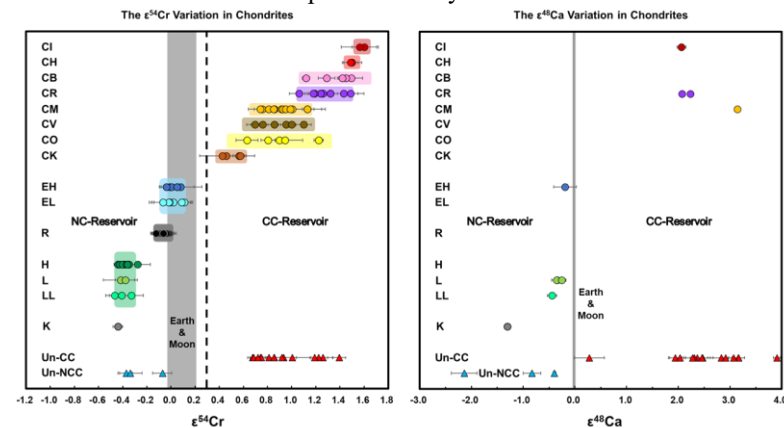


Figure 1 The $\epsilon^{54}\text{Cr}$ and $\epsilon^{48}\text{Ca}$ variation of ungrouped chondrites and other Solar System materials. Red and blue triangles are ungrouped carbonaceous (Un-CC) and non-carbonaceous chondrites (Un-NCC) respectively. The grey bars represent the Earth and Moon values.

In **figure 2**, we demonstrate the relationship between $\epsilon^{54}\text{Cr}$, $\epsilon^{50}\text{Ti}$ and $\epsilon^{48}\text{Ca}$ data. For the NC reservoir, most of the parent bodies have positively correlated $\epsilon^{54}\text{Cr}$ and $\epsilon^{50}\text{Ti}$ values (**Figure 2b**). We will discuss the following four groups of meteorites in more details: OCs, angrites, Vesta and acapulcoites. OCs and angrites share similar $\epsilon^{54}\text{Cr}$ values, but they have distinct $\epsilon^{50}\text{Ti}$ values, while angrites, Vesta and acapulcoites have similar $\epsilon^{50}\text{Ti}$ compositions, but angrites show different $\epsilon^{54}\text{Cr}$ values from Vesta and acapulcoites. As for CCs, $\epsilon^{50}\text{Ti}$ and $\epsilon^{54}\text{Cr}$ show a negative correlation. $\epsilon^{50}\text{Ti}$ and $\epsilon^{54}\text{Cr}$ values of the five ungrouped CCs in this study and [2] do not strongly correlate.

$\epsilon^{48}\text{Ca}$ and $\epsilon^{54}\text{Cr}$ values of the meteorites measured here do not correlate, which is mostly influenced by the samples with $\epsilon^{54}\text{Cr} = \sim -0.4$, i.e., OCs, KC, angrites, winonaite, MIL 15362 and NWA 5717 that have largely different $\epsilon^{48}\text{Ca}$ values. Previously measured $\epsilon^{48}\text{Ca}$ values [6, 10] exhibited a relationship with $\epsilon^{54}\text{Cr}$ values for different Solar System parent bodies, in a similar way as $\epsilon^{50}\text{Ti}$, i.e., positive and negative correlation in NC and CC materials respectively. However, when considering the $\epsilon^{48}\text{Ca}$ and $\epsilon^{54}\text{Cr}$ data for the ungrouped

chondrites, this correlation between $\epsilon^{48}\text{Ca}$ and $\epsilon^{54}\text{Cr}$ for NC and CC materials does not hold. Hence, the carrying phase for $\epsilon^{54}\text{Cr}$ anomaly is mostly different from that of $\epsilon^{50}\text{Ti}$ and $\epsilon^{48}\text{Ca}$.

The relationship between $\epsilon^{50}\text{Ti}$ and $\epsilon^{48}\text{Ca}$ has been suggested to be controlled by a common carrying phase, mostly perovskite (CaTiO_3), based on a well-defined correlation line (slope = ~ 1) between $\epsilon^{50}\text{Ti}$ and $\epsilon^{48}\text{Ca}$ values [9]. However, when only high precision $\epsilon^{48}\text{Ca}$ data produced by MC-ICP-MS (precision of 5 to 20 ppm, [6,10] (vs. 20-70 ppm in [9]) are considered (**Figure 2d**), the correlation between $\epsilon^{50}\text{Ti}$ and $\epsilon^{48}\text{Ca}$ values does not stand. In detail, in the NC region, NWA 5717 clearly fall out the potential correlation line of $\epsilon^{50}\text{Ti}$ and $\epsilon^{48}\text{Ca}$ values. Neither are CR chondrites and MAC 88107 in CC region. Also, MAC 87300 [ungrouped C2] and MAC 87301 [ungrouped C3] (they are not paired meteorites) have similar $\epsilon^{48}\text{Ca}$ (and also $\epsilon^{54}\text{Cr}$) values, but different $\epsilon^{50}\text{Ti}$ values [2]. Therefore, when considering the higher precision $\epsilon^{48}\text{Ca}$ data for the ungrouped chondrites, the well-defined correlation line between $\epsilon^{50}\text{Ti}$ and $\epsilon^{48}\text{Ca}$ values described in [9] does not stand, and the carrying phases for the ^{50}Ti and ^{48}Ca anomalies may have different origins [e.g., 12] and not limited to one mineral, e.g., perovskite.

We will discuss the chondrite grouping from $\epsilon^{48}\text{Ca}$ and $\epsilon^{54}\text{Cr}$ data in the final publication of this work.

Figure 3 represents the ^{26}Al - ^{26}Mg plot for all chondrites, including the literature data. There is no ^{26}Al - ^{26}Mg correlation line or isochron, even if the CR chondrites were excluded [13]. MIL 07513 possesses the highest $^{27}\text{Al}/^{24}\text{Mg}$ ratio and $\mu^{26}\text{Mg}^*$ value among all the chondrites, which may be related to its highest $\epsilon^{48}\text{Ca}$ values (3.91 ± 0.07), consistent with a CAI mixing model [13], since CAIs have high Al/Mg ratios, high Ca content and high $\epsilon^{48}\text{Ca}$ values, up to ~ 6.3 [12]. It can be also supported by CV chondrites, with high CAI content, have higher Al/Mg ratio and $\epsilon^{48}\text{Ca}$ value than most other chondrites. However, lack of ^{26}Al - ^{26}Mg correlation excludes this two-endmember (CAI-chondrite) mixing model. Relative to matrix, chondrules experienced high-temperature melting and evaporation processes, usually have elevated $^{27}\text{Al}/^{24}\text{Mg}$ ratios (compared to bulk) that can be up to ~ 0.27 [e.g., 14]. Hence, chondrules and matrix can be other reservoirs that also influence on the ^{26}Al - ^{26}Mg plot for bulk chondrites [5].

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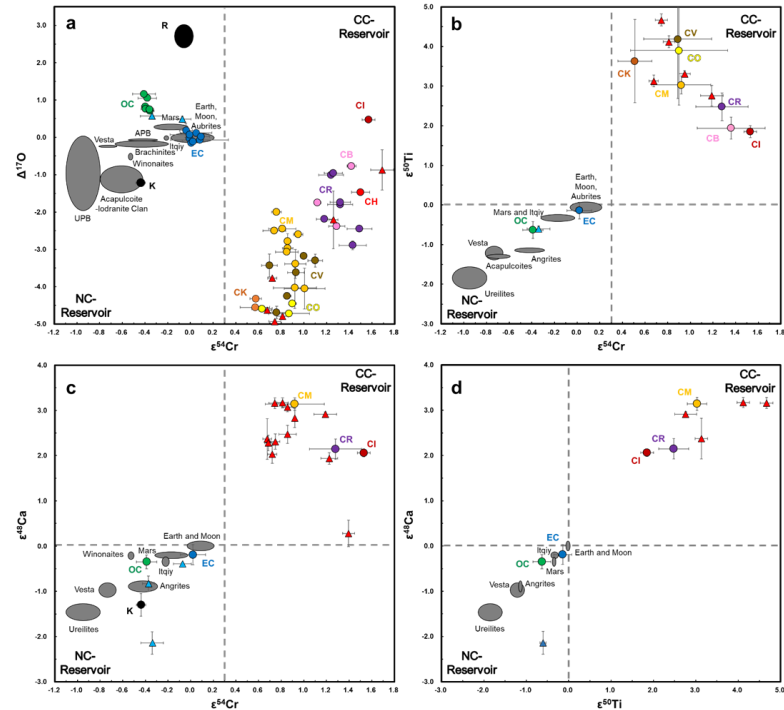


Figure 2 The relationships between $\Delta^{17}\text{O}$, $\varepsilon^{54}\text{Cr}$, $\varepsilon^{50}\text{Ti}$ and $\varepsilon^{48}\text{Ca}$ values for various Solar System materials. Colorful circles are chondrites, same as those in Figure 1, while the grey areas represent the differentiated planetary bodies. The dashed lines are the boundaries of CC and NC material.

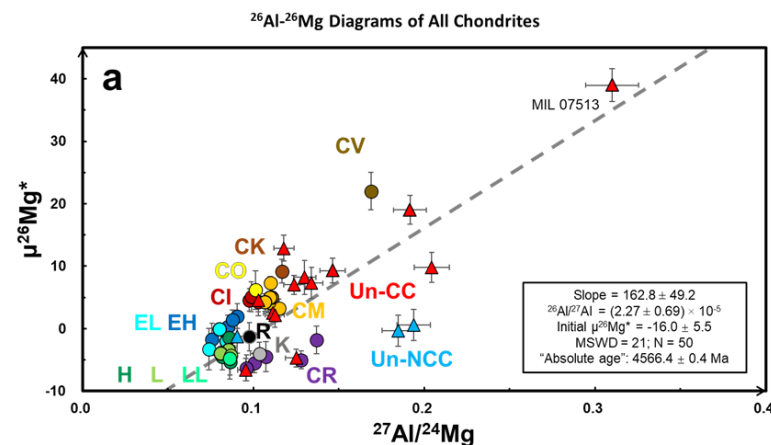


Figure 2 The ^{26}Al - ^{26}Mg plot for all the chondrites.

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