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# Mass-independent and mass-dependent Cr isotopic composition of the Rumuruti (R) chondrites: Implications for their origin and planet formation

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## 23 **Abstract**

24 Chromium (Cr) isotopes play an important role in cosmochemistry and planetary  
25 science, because they are powerful tools for dating ( $^{53}\text{Mn}$ - $^{53}\text{Cr}$  short-lived  
26 chronometry), tracing ( $^{54}\text{Cr}$  nucleosynthetic anomalies) the origins of the materials,  
27 and studying the processes involved in volatile element fractionation and planetary  
28 differentiation (Cr stable isotopic fractionation). The foundation for using Cr isotopes  
29 is to precisely know the compositions of the various chondritic reservoirs. However,  
30 the Cr isotope composition of Rumuruti (R) chondrites remains unknown. Here, we  
31 report high-precision mass-independent (average 2SE uncertainty of  $\sim 0.02$  and  $\sim 0.06$   
32 for  $\epsilon^{53}\text{Cr}$  and  $\epsilon^{54}\text{Cr}$ , respectively;  $\epsilon$  indicates 10,000 deviation) and mass-dependent  
33 (uncertainty of average  $0.03\text{‰}$  for  $\delta^{53}\text{Cr}$ ;  $\delta$  indicates 1,000 deviation) Cr isotope data  
34 for 12 bulk R chondrites of petrologic types 3-6 (included R chondrite breccias), and  
35 one R chondrite-like clast (MS-CH) in the Almahata Sitta polymict ureilite. All the R  
36 chondrites show homogeneous bulk  $\epsilon^{54}\text{Cr}$  values,  $-0.06 \pm 0.08$  (2SD), similar only to  
37 those of the Earth-Moon system and enstatite chondrites. These first  $\epsilon^{54}\text{Cr}$  data for R  
38 chondrites provide significant addition to the  $\epsilon^{54}\text{Cr}$ - $\Delta^{17}\text{O}$  diagram, and position them as  
39 a potential endmember for planetary precursors. The R chondrites possess a higher  
40  $^{55}\text{Mn}/^{52}\text{Cr}$  of  $0.68 \pm 0.04$  and higher  $\epsilon^{53}\text{Cr}$  values  $0.23 \pm 0.05$  (2SD) relative to most of  
41 other chondrite groups. This likely results from the lower (e.g. than ordinary and  
42 enstatite chondrites) chondrule abundance in R chondrites. The stable Cr isotope

43 composition of R chondrites is homogeneous with a  $\delta^{53}\text{Cr} = -0.12 \pm 0.03 \text{ ‰}$  (2SD).  
44 Combined with previous data of other groups of chondrites, we show that the stable Cr  
45 isotopic composition of all the chondrites is homogeneous with  $\delta^{53}\text{Cr}$  of  $-0.12 \pm 0.04 \text{ ‰}$   
46 (2SD, N = 40) and is independent of the petrologic type and redox conditions. The lack  
47 of **mass-dependent** fractionation between all groups of chondrites **suggests** that the  
48 average chondrite  $\delta^{53}\text{Cr}$  value is also representative for the initial composition all  
49 differentiated planets in the Solar System. Finally, the MS-CH clast in Almahata Sitta  
50 has a Cr isotopic composition ( $\epsilon^{53}\text{Cr} = 0.18 \pm 0.04$ ,  $\epsilon^{54}\text{Cr} = -0.16 \pm 0.07$ , and  $\delta^{53}\text{Cr} =$   
51  $-0.11 \pm 0.05 \text{ ‰}$ ) that is consistent (within error) with it being an R chondrite-like clast.

52

53

## 54 1. Introduction

55 Chondrites which contain chondrules, matrix, Fe-Ni metal and refractory  
56 inclusions, are the most primitive rocks in the Solar System available to us (e.g., Krot  
57 et al., 2014). Because they did not melt and differentiate, they may record the  
58 information of evolution of early Solar System. Chondrites also have a bulk chemical  
59 composition that is thought to be representative of their parent bodies, and are often  
60 used to approximate the compositions of the building blocks of the terrestrial planets  
61 such as the Earth (e.g., Allègre et al., 1995). Amongst the chondrites, the Rumuruti (R)  
62 chondrites are only recognized as a new group and class in 1994 (Bischoff et al., 1994;  
63 Kallemeyn et al., 1996; Rubin and Kallemeyn, 1994; Schulze et al., 1994). The physical  
64 and chemical features of the R chondrites are reviewed in detail by Bischoff et al.  
65 (2011).

66 Unlike other chondrites, including carbonaceous (CC), ordinary (OC) and  
67 enstatite chondrites (EC), the R chondrites have some unusual or characteristic features :  
68 1) most of the R chondrites are breccias that contain clasts with various degree of  
69 metamorphism; 2) they have high abundances of olivine (70 vol.%); 3) matrix and  
70 chondrules have similar abundances; 4) they formed under high oxygen fugacity  
71 conditions as demonstrated by the absence of Fe-Ni metal; 5) the size of chondrules are  
72 on average ~400 µm; 6) they have element (except for Zn and Se) abundances that are  
73 similar to those in ordinary chondrites (~0.95 times of CI chondrites); 7) they have high

74 TiO<sub>2</sub> contents in the Cr-spinels; 8) Ca-Al-rich inclusions (CAIs) are rare (Rout and  
75 Bischoff, 2008; Rout et al., 2009, 2010); 9) they have higher  $\Delta^{17}\text{O}$  (mass-independent  
76  $^{17}\text{O}/^{16}\text{O}$  isotope ratios;  $2.72 \pm 0.31$ ) compositions than all the other chondrite groups; 10)  
77 very primitive type 3 lithologies only exist as clasts in R chondrite breccias (Bischoff,  
78 2008); 11) within the most primitive type 3 lithologies the chondrule-matrix  
79 complementary is well defined (Friend et al., 2017).

80 Combining  $\Delta^{17}\text{O}$  with  $\epsilon^{54}\text{Cr}$  (the parts per 10,000 deviation of the mass  
81 fractionation corrected  $^{54}\text{Cr}/^{52}\text{Cr}$  ratio from a terrestrial standard) is a powerful tool for  
82 establishing relationships between Solar System materials (Clayton and Mayeda, 1999;  
83 Trinquier et al., 2007; Warren, 2011). All known bulk Solar System materials belong to  
84 one of two reservoirs: carbonaceous-chondrite (CC) with  $\epsilon^{54}\text{Cr}$  value  $> 0.3$  and  
85 non-carbonaceous-chondrite (NC) with  $\epsilon^{54}\text{Cr}$  value  $< 0.3$  (Qin et al., 2010; Trinquier et  
86 al., 2007). However, the  $\epsilon^{54}\text{Cr}$  values for R chondrites are still poorly known. One of  
87 only two R chondrites with previously reported  $\epsilon^{54}\text{Cr}$  values [ $0.43 \pm 0.09$ , Elephant  
88 Moraine [EET] 96026 (Qin et al., 2010)] has since been re-classified as a CV3 or an  
89 ungrouped C4/5 chondrite (Meteoritical Bulletin Database;  
90 <https://www.lpi.usra.edu/meteor>). The only other measured R chondrite, Northwest  
91 Africa [NWA] 753 (R3.9),  $-0.11 \pm 0.25$  (Larsen et al., 2011), has a large uncertainty that  
92 spans the  $\epsilon^{54}\text{Cr}$  values of both OCs and ECs. Furthermore, just one measured sample  
93 cannot safely be taken to represent the R chondrite parent body, since there could be  
94 some degree of  $\epsilon^{54}\text{Cr}$  variability within a chondrite parent body as already observed for

95 CV, CO, and CM chondrites (Qin et al., 2010; Trinquier et al., 2007). Apart from the  
96 one relatively imprecise  $\epsilon^{54}\text{Cr}$  measurement, no other iron-group neutron-rich  
97 nucleosynthetic isotope data has been reported for the R chondrites (e.g., Ca, Ti and Ni  
98 isotope anomalies). Since the R chondrites are non-carbonaceous chondrites (NCs),  
99 studying their  $\epsilon^{54}\text{Cr}$  composition can also be used to further test, whether the NCs all  
100 have different Cr isotopic composition than the carbonaceous chondrites (e.g., Göpel et  
101 al., 2015; Sanborn et al., 2019; Trinquier et al., 2007; Warren, 2011).

102 The variations in the abundance of  $^{53}\text{Cr}$  (expressed as  $\epsilon^{53}\text{Cr}$ ) mostly result from the  
103 decay of  $^{53}\text{Mn}$ , with a half-life of 3.7 Ma (Holden, 1990; Honda and Imamura, 1971).  
104 The  $^{53}\text{Cr}$  is a sensitive tracer of the timing of formation of the chondrites and their  
105 components, and the differentiation of planetesimals and planets (Lugmair and  
106 Shukolyukov, 1998; Shukolyukov and Lugmair, 2006). For example, the  $^{53}\text{Mn}$ - $^{53}\text{Cr}$   
107 short-lived chronometry has been successfully used to date the accretion of chondrite  
108 parent bodies (Trinquier et al., 2008) and formation of chondrules (Nyquist et al., 2001;  
109 Yamashita et al., 2010; Yin et al., 2007; Yin et al., 2009; Zhu et al., 2019a; Zhu et al.,  
110 2020a) of which ages potentially represent the earliest accretion ages of their host  
111 chondrites. Therefore, the  $\epsilon^{53}\text{Cr}$  values of the R chondrites may also provide significant  
112 information about the origin of their parent body(ies), as well as its possible  
113 relationship to differentiated achondrite parent bodies.

114 The Cr stable isotopes (expressed as  $\delta^{53}\text{Cr}$ , the per mil variation of the  $^{53}\text{Cr}/^{52}\text{Cr}$   
115 ratio relative to a terrestrial standard, NIST SRM 979) is a tracer of planetary evolution,

116 including volatile depletion (Sossi et al., 2018; Zhu et al., 2019c), magmatic processes  
117 (Bonnand et al., 2020; Bonnand et al., 2016a; Shen et al., 2019; Sossi et al., 2018; Zhu  
118 et al., 2019c), and possibly core formation (Moynier et al., 2011). However, an  
119 unknown is the starting isotope composition of the material before fractionation, i.e.,  
120 those of the planetary precursors. It is therefore important to investigate the presently  
121 unknown Cr stable isotopic composition of the R chondrites, including the various  
122 petrologic types (from R3 to R6).

123 Here, we report high-precision mass-independent and mass-dependent Cr isotope  
124 data for 12 bulk R chondrites that sample the full range of petrologic types (3-6) and  
125 one R chondrite-like clast from a polymict ureilite, Almahata Sitta. We use the  
126 radiogenic and nucleosynthetic Cr isotope anomalies and Cr stable isotope  
127 compositions of the R chondrites to discuss their possible relationship with other  
128 chondrites and achondrites. The Cr isotope composition of the R chondrite-like clast  
129 within the polymict ureilite Almahata Sitta (Bischoff et al., 2010; Horstmann and  
130 Bischoff 2014) is used to test whether this clast is indeed related to R-chondrites, and  
131 further track the potential transport processes and dynamics (from a chondrite parent  
132 body to an achondrite parent body) in the early Solar System.

## 133 **2. Samples and analytical methods**

### 134 **2.1 Sample information and dissolution**

135 The sample suite analyzed in this study includes 12 bulk R chondrites: Rumuruti



136 (R3.8-6), Pecora Escarpment (PCA) 91002 (R3.8-6), LaPaz Icefield (LAP) 03645 (R),  
137 NWA 1476 (R3), NWA 2446 (R3), NWA 753 (R3.9), Miller Range (MIL) 07440 (R4),  
138 LAP 03639 (R4), NWA 053 (R4), NWA 6145 (R5), MIL 11207 (R6) and LAP 04840  
139 (R6). We also analyzed one R chondrite-like clast named MS-CH in Almahata Sitta  
140 (polymict ureilite). It has previously been described by Horstmann et al. (2010) and  
141 reviewed in (Bischoff et al., 2010). In summary, this clast weighs 5.68g, possess ~400  
142  $\mu\text{m}$  chondrules, 40 vol.% of matrix and a  $\Delta^{17}\text{O}$  value of  $\sim 1.7\text{‰}$ , which are all similar  
143 properties to those of R chondrites. To assess the data quality, we also measured the  
144 USGS rock standards **DTS-2b**, **PCC-1** and **BHVO-2**.

145 **R chondrite samples with no fusion crusts weighing 0.5 to 1 g were crushed to a**  
146 **fine powder using a boron carbide mortar and pestle. A fraction of the powders (ca.**  
147 **100 mg) were digested by sequential mixtures of concentrated HF+HNO<sub>3</sub> (2:1) and**  
148 **HNO<sub>3</sub> + HCl (1:3) in Parr Bombs under pressurized steel jackets for 3-4 days at 180 °C**  
149 **respectively, and no visible residues were observed. Then, ~1%, ~5% and ~5%**  
150 **aliquots were extracted for measurements of <sup>55</sup>Mn/<sup>52</sup>Cr ratios, mass-independent and**  
151 **mass-dependent Cr isotope fractionation, respectively. The rest of the solution is kept**  
152 **for other chemical and isotopic analysis.**

## 153 **2.2 Mass-independent Cr isotope ( $\epsilon^{53}\text{Cr}$ and $\epsilon^{54}\text{Cr}$ ) measurements**

154 A four-step column chemistry was used to purify the sample for  
155 mass-independent Cr isotope measurements in a clean laboratory at Earth and  
156 Planetary Laboratory, Carnegie Institute for Science. Firstly, we used an anion

157 chromatographic purification column to efficiently remove Fe and Ni in 6M HCl. Prior  
158 to sample loading on cation exchange columns, we used a Cr pre-treatment procedure  
159 involving dissolution in 10M HCl at >120 °C to efficiently promote the formation of  
160 Cr<sup>3+</sup>-Cl species, which have a low affinity for the cation exchanger and thus elute early.  
161 This was followed by elution of Cr on a 1 ml cation exchange column in 20 ml of 0.5M  
162 HNO<sub>3</sub> to remove the major elements, including Mg, Ca, Al, and Ni, and to collect all  
163 the Cr species (major Cr<sup>0</sup> and minor Cr<sup>2+</sup> and Cr<sup>3+</sup>) to reach a >99% recovery. The  
164 samples were then exposed to 0.5M HNO<sub>3</sub> + 0.6% H<sub>2</sub>O<sub>2</sub> at room temperature for >1  
165 day to promote the formation of Cr<sup>3+</sup> (Larsen et al., 2016). However, it is difficult to  
166 transform all Cr to Cr<sup>3+</sup>, so the Cr<sup>0</sup>-bearing material is collected in 0.5 ml of the loading  
167 solution and 0.5 ml of 0.5N HNO<sub>3</sub> elution to increase the recovery to >95% in the next  
168 column. The third clean-up column involved Cr purification from Al, Ti, V, and Fe (and  
169 other high-field-strength elements), as well as Na and K, on a small (0.33ml) cation  
170 exchange column using 0.5M HNO<sub>3</sub>, 1M HF, and 6M HCl. Finally, for the fourth  
171 column, 0.7 ml of TODGA resin was used in 8N HCl to remove the residual Fe, V, and  
172 Ti (which remained on the column) that have isobaric isotopes with <sup>54</sup>Cr (<sup>54</sup>Fe) and <sup>50</sup>Cr  
173 (<sup>50</sup>V and <sup>50</sup>Ti) (Pedersen et al., 2019). The full procedure reaches a total yield of  
174 between 95% and 99%, and effectively removes any matrix, especially Fe, V, and Ti,  
175 that might influence analysis by Multiple Collector-Inductively Coupled Plasma-Mass  
176 Spectrometry (MC-ICP-MS). The total blank of the isolation procedure is 10-12 ng for  
177 Cr and can be neglected given the typical sample size, ~10 µg of Cr.

178 The  $^{55}\text{Mn}/^{52}\text{Cr}$  ratios were measured on a MC-ICP-MS Neptune Plus. We  
179 initially prepared three Mn-Cr doped artificial standard solutions gravitationally, with  
180 Mn-Cr contents of 10–100 ppb, 50–100 ppb and 100–100 ppb and Mn/Cr ratios of 0.1,  
181 0.5 and 1.0. The unpurified sample solutions were diluted to a Cr content of ~100 ppb.  
182 The intensities for  $^{55}\text{Mn}$  and  $^{52}\text{Cr}$  on faraday detectors obtained when analyzing the  
183 standard and sample solutions ranged from 0.5 V to 5 V, and 10 cycles of 4 seconds  
184 each were measured in each analysis to obtain a target precision for the  $^{55}\text{Mn}/^{52}\text{Cr}$  ratios  
185 better than 1%. After establishing a calibration curve ( $R^2 > 0.999$ ) based on the true and  
186 measured  $^{55}\text{Mn}/^{52}\text{Cr}$  ratios of the three artificial standards, the  $^{55}\text{Mn}/^{52}\text{Cr}$  ratios of the  
187 chondrite samples could be calculated. The final estimated precision is <5% (Zhu et al.,  
188 2020a; Zhu et al., 2020b).

189 Compared to Thermal Ionization Mass Spectrometry (TIMS), chromium isotope  
190 analysis by MC-ICP-MS has the advantage that the high ionization efficiency of the  
191 plasma results in relative constant mass fractionation, which by use of the  
192 sample-standard-bracketing approach can be well corrected for and essentially  
193 eliminates the need for consideration of the instrumental mass fractionation. Thermal  
194 ionization, on the other hand, inherently does not produce stable mass fractionation  
195 through time, which may cause a residual, apparent mass-dependent effect after mass  
196 fractionation correction by exponential law (assuming kinetic fractionation), which is  
197 demonstrated by the correlation between  $\epsilon^{53}\text{Cr}$  and  $\epsilon^{54}\text{Cr}$  with slope of ~2.6 of Cr  
198 isotope standards (Qin et al., 2010; Trinquier et al., 2006). This effect ultimately limits

199 both the obtainable accuracy and precision of mass fractionation corrected isotope  
200 data obtained by TIMS. Therefore, Cr isotope analysis by MC-ICP-MS can achieve  
201 higher data precision than by TIMS for comparable measurement signal and time but  
202 typically requires larger amount of sample due to the lower transmission efficiency of  
203 the MC-ICP-MS (e.g., Pedersen et al., 2019; Schiller et al., 2014; Zhu et al., 2020b).

204 The Cr isotopic compositions of all the samples were determined using one of  
205 the MC-ICP-MS Neptune Plus located at the Centre for Star and Planet Formation,  
206 Globe Institute, University of Copenhagen. Detailed analytical and data reduction  
207 methods are described elsewhere (Pedersen et al., 2019; Schiller et al., 2014; Zhu et  
208 al., 2020b). The Cr isotopic composition of each sample was measured by  
209 sample-standard bracketing using the NIST SRM 979 Cr standard. Sample solutions  
210 with ~0.5 ppm Cr were introduced to the plasma via an ESI Apex IR resulting in  $^{52}\text{Cr}$   
211 signals of 20-40 V at an uptake rate of ~0.06 mL/min. Each sample was measured five  
212 times and the resulting average 2 standard error (2se) uncertainty for  $\epsilon^{53}\text{Cr}$  and  $\epsilon^{54}\text{Cr}$   
213 are ~0.02 and ~0.06, respectively. The  $^{53}\text{Cr}/^{52}\text{Cr}$  and  $^{54}\text{Cr}/^{52}\text{Cr}$  ratios were normalized  
214 to a constant  $^{50}\text{Cr}/^{52}\text{Cr}$  ratio of 0.051859 using the exponential law (Lugmair and  
215 Shukolyukov, 1998). All the measured isotopic ratios are expressed relative to NIST  
216 SRM 979 in the epsilon notations:

$$217 \quad \epsilon^{x\text{Cr}} = \left( \frac{(^{x\text{Cr}}/^{52}\text{Cr})_{\text{sample}}}{(^{x\text{Cr}}/^{52}\text{Cr})_{\text{NIST SRM 979}}} - 1 \right) \times 10000 \quad (1),$$

218 with  $x = 53$  or  $54$ .

## 219 **2.3 Mass-dependent Cr isotope ( $\delta^{53}\text{Cr}$ ) measurements**

220 The whole procedure of mass-dependent Cr isotope analysis was performed at  
221 the Institut de Physique du Globe de Paris (IPGP) on aliquots of the same dissolutions  
222 used for mass-independent isotope measurements. This measurement techniques  
223 followed the same procedure as described in Sossi et al. (2018) and Zhu et al. (2019c).  
224 First, the appropriate amount of  $^{50}\text{Cr}$ - $^{54}\text{Cr}$  double spike (28% of the Cr content endemic  
225 to the sample) was added to the aliquot, which was then refluxed in a closed beaker at  
226 120 °C overnight to homogenize the sample and spikes (e.g., Wu et al., 2020). Then,  
227 samples were chemically purified for Cr via a two-step cation exchange  
228 chromatography followed by previous works (Sossi et al., 2018; Zhu et al., 2019c).  
229 This method has a total procedural yield of 60-90% and a blank of ~5 ng of Cr.  
230 Compared to the total ~10  $\mu\text{g}$  of Cr, the blank can be neglected. The final Cr cut was  
231 evaporated in concentrated  $\text{HNO}_3$  drops 3 to 5 times to convert the HCl medium to  
232  $\text{HNO}_3$  and to remove leftover organics (i.e., the resin) following which the samples  
233 were diluted to a concentration of 1 ppm Cr, in 2% (0.317 M)  $\text{HNO}_3$  for isotope  
234 analysis.

235 The Cr stable isotope compositions of these purified samples were measured on a  
236 Thermo Scientific Neptune Plus MC-ICP-MS housed at the IPGP. Analytical details  
237 are described in Sossi et al. (2018) and Zhu et al. (2019c). The final Cr stable isotope  
238 data ( $\delta^{53}\text{Cr}$ ) for R chondrites were corrected taking their respective mass-independent

239 Cr isotope compositions analyzed on the same aliquots. The isotopic ratio for samples  
240 is reported in delta notation relative to NIST SRM 979:

$$241 \quad \delta^{53}\text{Cr}(\text{‰}) = \left( \frac{(^{53}\text{Cr}/^{52}\text{Cr})_{\text{sample}}}{(^{53}\text{Cr}/^{52}\text{Cr})_{\text{NIST SRM 979}}} - 1 \right) \times 1000. (2)$$

242 The uncertainties quoted for individual samples are 2SD of single sample  
243 measurements (100 cycles for at least two times) or 2SD reproducibility of several  
244 NIST SRM 979 measurements in the same analytical session ( $\sim 0.02 \text{ ‰}$ ), whichever is  
245 the largest.

### 246 **3. Results**

247 All the Mn/Cr ratios, mass-independent and mass-dependent Cr isotope data for  
248 the 12 bulk R chondrites and the clast MS-CH from the meteorite/asteroid Almahata  
249 Sitta are reported in Table 1. The  $\epsilon^{54}\text{Cr}$  values for all R chondrites are homogeneous,  
250 with an average value of  $-0.06 \pm 0.08$  (2SD, N = 12) (Figures 1 and 2). All the R  
251 chondrites have a restricted range of  $^{55}\text{Mn}/^{52}\text{Cr}$  ratios of  $0.68 \pm 0.04$  (2SD, except NWA  
252 2446 which has a  $^{55}\text{Mn}/^{52}\text{Cr}$  of 0.60), but have different  $\epsilon^{53}\text{Cr}$  values ranging from  $0.19$   
253  $\pm 0.02$  to  $0.27 \pm 0.02$  (Figure 3a, b), averaging at  $0.23 \pm 0.05$  (2SD, N = 12). There is no  
254 correlation between the  $^{55}\text{Mn}/^{52}\text{Cr}$  ratios and the  $\epsilon^{53}\text{Cr}$  values (Figure 3b). The  
255 R-chondrite-like clast, MS-CH, possesses  $\epsilon^{53}\text{Cr} = 0.18 \pm 0.04$  and  $\epsilon^{54}\text{Cr} = -0.16 \pm 0.07$   
256 that are indistinguishable within uncertainties to those of the R chondrites. Also, all the  
257 R chondrites possess homogeneous stable Cr isotope compositions (Figure 4), with an

258 average  $\delta^{53}\text{Cr} = -0.12 \pm 0.03 \text{ ‰}$  (2SD, N = 12) that is indistinguishable to that of  
259 MS-CH with  $\delta^{53}\text{Cr}$  of  $-0.11 \pm 0.05 \text{ ‰}$ .

260 The mass-independent Cr isotope data for **PCC-1 and DTS-2b** in this study are  
261 consistent with literature data (Qin et al., 2010; Schiller et al., 2014; Trinquier et al.,  
262 2007; Trinquier et al., 2008; Zhu et al., 2019b; Zhu et al., 2020b).

263 The mass-dependent  $\delta^{53}\text{Cr}$  data (measured by double spike technique) for  
264 **BHVO-2 and PCC-1** are also consistent with the literature data (Bonnand et al., 2016b;  
265 Liu et al., 2019; Schoenberg et al., 2016; Sossi et al., 2018; Wu et al., 2020; Zhu et al.,  
266 2019c).

## 267 **4. Discussion**

### 268 **4.1 Homogeneous $\epsilon^{54}\text{Cr}$ in R chondrites**

269 Cosmogenic effects, especially in samples with high Fe/Cr ratios and cosmic ray  
270 exposure ages (CREA), can modify the Cr isotope composition (e.g., Shima and  
271 Honda, 1966). The R chondrites have lower Fe/Cr ratios of  $\sim 105$  (Kallemeyn et al.,  
272 1996; Schulze et al., 1994) and similar CREA of 0.1~74 Ma (Schultz et al., 2005)  
273 relative to angrites (Fe/Cr = 70-700; CREA = 6-70 Ma) that do not show any  
274 cosmogenic effects (Zhu et al., 2019b). Moreover, the  $\epsilon^{54}\text{Cr}$  for all the R chondrites  
275 irrespective of their exposure age are indistinguishable from each other, such that the Cr  
276 isotope alteration from cosmogenic effects, if present, are currently not detectable and,  
277 thus, can be ignored.

278 As a group/class of NCs, the homogeneous  $\epsilon^{54}\text{Cr}$  value of the R chondrites of  
279  $-0.06 \pm 0.08$  (2SD, N = 12; Figures 1 and 2) confirms the observation that there is a Cr  
280 isotopic difference between the NCs ( $\epsilon^{54}\text{Cr} < 0.3$ ) and the CCs ( $\epsilon^{54}\text{Cr} > 0.3$ ) (Qin et al.,  
281 2010; Trinquier et al., 2007). The  $\epsilon^{54}\text{Cr}$  values for R chondrites are similar within  
282 error to those of the ECs [ $\epsilon^{54}\text{Cr} = 0.01 \pm 0.11$ ; 2SD, N = 12; (Mougel et al., 2018; Qin  
283 et al., 2010; Trinquier et al., 2007; Zhu et al., 2020a)]. We can use this new value to  
284 update the  $\epsilon^{54}\text{Cr}$  sequence between the different groups of chondrites (Figure 1) to be:  
285 **CC > EC = RC > OC** (Göpel et al., 2015; Mougel et al., 2018; Qin et al., 2010;  
286 Trinquier et al., 2007). It should be noted that the average  $\epsilon^{54}\text{Cr}$  value for R chondrites  
287 also overlaps within error with those of the Earth [ $\epsilon^{54}\text{Cr} = 0.09 \pm 0.12$ ; 2SD, N=14,  
288 (Mougel et al., 2018; Trinquier et al., 2007)], Moon [ $\epsilon^{54}\text{Cr} = 0.09 \pm 0.08$ ; (Mougel et al.,  
289 2018)] and one aubrite meteorite [ $\epsilon^{54}\text{Cr} = -0.16 \pm 0.19$ ; {Trinquier, 2007 #139}]. **Other**  
290 **than the  $\epsilon^{54}\text{Cr}$  features**, the R chondrites also formed with oxygen **fugacities** [FMQ -4 ~  
291 FMQ 0 **oxygen** buffer; (Righter and Neff, 2007)] that were much closer to the Earth's  
292 upper mantle value [ $f\text{O}_2 = \text{FMQ} -4 \sim \text{FMQ} +2$ ; (McCammon, 2005)] compared to the  
293 much more reduced ECs [FMQ -8 ~ -10; (Righter et al., 2006)] that are more  
294 commonly proposed as major building blocks of the Earth (Javoy et al., 2010).  
295 However, the R chondrites have much higher  $\Delta^{17}\text{O}$  values [ $\sim 2.7$  (Bischoff et al., 2011;  
296 Schulze et al., 1994; Weisberg et al., 1991)] than the Earth-Moon system [ $\sim 0$ ; (Cano et  
297 al., 2020; Clayton and Mayeda, 1996; Greenwood et al., 2018; Pack and Herwartz,  
298 2014; Wiechert et al., 2001; Young et al., 2016); Figure 2] and the Mg/Si and Al/Si of



299 the R chondrites do not match those of the bulk Earth (Alexander, 2019b). Therefore,  
300 while their Cr isotopic composition and oxidation state match the Earth, the R  
301 chondrites or their precursors cannot **totally** represent the building materials for the  
302 Earth-Moon system. Nevertheless, in  $\epsilon^{54}\text{Cr}-\Delta^{17}\text{O}$  space (Figure 2) the R chondrites  
303 define an end member and should, therefore, be considered in mixing models for  
304 planetary precursors (e.g., Alexander, 2019a; Alexander, 2019b; Dauphas, 2017). It is  
305 also clear that the R chondrites have distinct  $\epsilon^{54}\text{Cr}$  values from those of the OCs [ $\epsilon^{54}\text{Cr}$   
306 =  $-0.39 \pm 0.09$ ; (2SD, N = 18; Pedersen et al., 2019; Qin et al., 2010; Trinquier et al.,  
307 2007)], suggesting that there is no genetic relationship between them, even though  
308 they have some affinities in terms of their bulk compositions (Alexander, 2019b;  
309 Kallemeyn et al., 1996; Palme et al., 1996).

310 The CB, CO, and CK chondrites all exhibit  $\epsilon^{54}\text{Cr}$  variability within each group  
311 (Figure 1) and even between several specimens of the same meteorite, e.g., Allende  
312 with  $\epsilon^{54}\text{Cr}$  values ranging from  $0.86 \pm 0.09$  (Trinquier et al., 2007) to  $1.10 \pm 0.08$  (Zhu  
313 et al., 2020b). These heterogeneities probably reflect heterogeneities in the  
314 abundances of isotopically extreme CAIs, amoeboid olivine aggregates (AOAs) [with  
315 high  $\epsilon^{54}\text{Cr}$  values, up to  $\sim 10$  (Trinquier et al., 2009)] and chondrules (Bollard et al.,  
316 2019; Olsen et al., 2016; Qin et al., 2011; Zhu et al., 2019a; Zhu et al., 2020a) at the  
317 scale of the samples analyzed. All measured R chondrites have similar  $\epsilon^{54}\text{Cr}$  values,  
318 which is consistent with the very low CAI abundances in R chondrites (Russell, 1998).  
319 Similar to the CK chondrites, OCs, and ECs that also experienced various degrees of

320 metamorphism, with petrological types of 3~6 (Pedersen et al., 2019; Qin et al., 2010;  
321 Trinquier et al., 2007), the  $\epsilon^{54}\text{Cr}$  values of the RCs are independent of petrologic types.  
322 This confirms that metamorphism on chondrite parent bodies did not cause the loss of  
323  $^{54}\text{Cr}$ -rich carrying phases (e.g., Dauphas et al., 2010; Nittler et al., 2018; Qin et al.,  
324 2011).

## 325 **4.2 The $^{53}\text{Mn}$ - $^{53}\text{Cr}$ systematics in R chondrites.**

326 It can be seen in Figure 3 that the R chondrites have almost uniform  $^{55}\text{Mn}/^{52}\text{Cr}$   
327 ratios (averagely  $\sim 0.68$ ) but variable  $\epsilon^{53}\text{Cr}$  values. The  $\epsilon^{53}\text{Cr}$  variation within the R  
328 chondrite parent body should result from the mixing of their chondritic components.  
329 Chondrites are complex assemblages, including CAIs, AOAs, chondrules, metals,  
330 sulfides, and matrix, and these different components formed at different times and  
331 under varying physical conditions (Krot et al., 2014). Refractory inclusions are scarce  
332 in R chondrites, i.e., CAIs + AOAs that are  $< 0.1$  vol.% (Bischoff et al., 2011; Krot et  
333 al., 2014), so the mixing of different proportion for chondrules and matrix may  
334 contribute to the  $\epsilon^{53}\text{Cr}$  variations. Chondrules are high-temperature magmatic objects  
335 and they or their precursors experienced volatile element fractionation (Mahan et al.,  
336 2018; Palme et al., 2014; Pringle et al., 2017) that caused Mn/Cr variability.  
337 Chondrules' redox history evolved with time, but globally they are reduced and  
338 probably formed at  $f\text{O}_2$  of iron-wüstite buffer (IW) -1 to -2 (Mahan et al., 2018),  
339 under which conditions Mn is more volatile than Cr (Sossi et al., 2019). This explains  
340 why chondrules have on average lower Mn/Cr ratios [e.g., CO chondrules with

341  $^{55}\text{Mn}/^{52}\text{Cr}$  ranging from 0.2-0.7; (Zhu et al., 2019a)] than unfractionated matrix that  
342 can be represented by CI chondrites with  $^{55}\text{Mn}/^{52}\text{Cr}$  of  $\sim 0.8$  (Qin et al., 2010;  
343 Trinquier et al., 2008) and on average lower  $\epsilon^{53}\text{Cr}$  [e.g., CO chondrules with  $\epsilon^{53}\text{Cr}$   
344 ranging from 0.0 to 0.2; (Zhu et al., 2019a)] than matrix representing by CI chondrites  
345 with  $\epsilon^{53}\text{Cr}$  of 0.20-0.25 (Qin et al., 2010; Trinquier et al., 2008). The bulk R  
346 chondrites, OCs and ECs all have similar Mn/Cr ratios, but the  $\epsilon^{53}\text{Cr}$  values of OCs  
347 and ECs are systematically lower than those of the R chondrite (Figure 3). This  $\epsilon^{53}\text{Cr}$   
348 difference between different chondrite groups may simply reflect the different  $\epsilon^{53}\text{Cr}$   
349 reservoirs in different chondrite accretion regions.

### 350 **4.3 Homogeneous $\delta^{53}\text{Cr}$ in R chondrites.**

351 Previous studies have shown that all the CCs, OCs, and ECs have homogeneous  
352 Cr stable isotope compositions,  $\delta^{53}\text{Cr} = -0.11 \pm 0.05 \text{‰}$  [2SD, N = 30; N<sub>CC</sub> = 11, N<sub>OC</sub>  
353 = 17, N<sub>EC</sub> = 2; (Bonnand et al., 2016b; Schoenberg et al., 2016)]. The  $\delta^{53}\text{Cr}$  values for  
354 all chondrites are similar to that of the bulk silicate Earth [ $\delta^{53}\text{Cr} = -0.11 \pm 0.06 \text{‰}$ ;  
355 2SD, N = 36; (Schoenberg et al., 2008; Sossi et al., 2018)], suggesting that core  
356 formation or volatile processes cause little Cr stable isotope fractionation, which is  
357 further supported by high-pressure metal-silicate experiments (Bonnand et al., 2016b).  
358 In this study, we found that the  $\delta^{53}\text{Cr}$  values for the R chondrites,  $-0.12 \pm 0.03 \text{‰}$  (2SD,  
359 N = 12), also fall in the chondrite-Earth  $\delta^{53}\text{Cr}$  range. This supports the view that, when  
360 corrected for their different nucleosynthetic signatures, the chondrite reservoirs have a  
361 homogeneous Cr stable isotope with  $\delta^{53}\text{Cr} = -0.12 \pm 0.04 \text{‰}$  (2SD, N = 42).

362 Different chondrites groups record different redox conditions (Rubin et al.,  
363 1988). In detail, the oxidized R and CV<sub>oxi</sub> chondrites record oxygen fugacities ( $fO_2$ ) of  
364 fayalite-magnetite-quartz buffer (FMQ)  $\sim$ -2, OCs have  $fO_2$  of FMQ  $\sim$ -6, and ECs are  
365 the most reduced, with  $fO_2$  of FMQ -8 to -10 (Righter et al., 2006; Righter and Neff,  
366 2007). The varied redox conditions for different chondrite groups correlate with their  
367 hydrogen isotope ratios (Alexander, 2019b), suggesting that the addition of water  
368 plays an important role in oxidation. The Cr stable isotope compositions of all these  
369 chondrites are homogeneous and, therefore, were not affected by parent body  $fO_2$   
370 conditions. This is perhaps surprising given the resolvable isotopic fractionation  
371 observed during  $Cr^{2+}/Cr^{3+}$  exchange in magmatic processes on the Earth (Bonnand et  
372 al., 2020; Shen et al., 2019), the Moon (Bonnand et al., 2016a; Sossi et al., 2018) and  
373 HEDs [(perhaps Vesta; (Zhu et al., 2019c)). However, it is firstly consistent with that  
374 water contained little Cr, which would not change the Cr species in chondrite parent  
375 body. Then, although it is possible that the presence of water oxidized Cr from  $Cr^{2+}$  to  
376  $Cr^{3+}$ , which may result in Cr stable isotope fractionation ( $Cr^{3+}$  would be isotopically  
377 heavier than  $Cr^{2+}$ ). However, in absence of loss of Cr via volatilization from the  
378 chondrite parent body, this effect would not lead to Cr isotope fractionation between  
379 chondrite groups. In any case, the homogeneous  $\delta^{53}Cr$  values between all chondrite  
380 groups strongly suggests that differentiated planets also had initial  $\delta^{53}Cr$  similar to  
381 chondrites, since chondrites are believed as their precursors (e.g., Allègre et al., 1995).  
382 The Cr stable isotopic difference between planetary mantles with different oxygen

383 **fugacities**, e.g., Earth [ $\delta^{53}\text{Cr} = -0.11 \pm 0.06$  (Schoenberg et al., 2008; Sossi et al.,  
384 2018)], Moon [ $\delta^{53}\text{Cr} = -0.21 \pm 0.03$  (Bonnand et al., 2016a; Sossi et al., 2018)] and  
385 HEDs (Vesta) [ $\delta^{53}\text{Cr} = -0.22 \pm 0.03$  (Zhu et al., 2019c)], is not due to variability in the  
386 initial composition but to planetary differentiation processes, e.g., volatile depletion  
387 and/or partial melting (Sossi et al., 2018; Zhu et al., 2019c).

388 The R chondrites with petrologic types ranging from 3 to 6 have homogeneous  
389  $\delta^{53}\text{Cr}$  values, suggesting that metamorphism does not affect the Cr isotopic  
390 composition of the bulk samples. In detail, metamorphism would not redistribute the  
391 Cr species inside chondrite parent bodies, which mimics the water effect as discussed  
392 above. Thus, in consequence, no differences were observed studying the Cr isotopic  
393 compositions of the brecciated rocks among the R chondrites. This is also consistent  
394 with the lack of resolvable Cr stable isotopic variability among metamorphic rocks  
395 (Shen et al., 2015; Wang et al., 2016), the  $\delta^{53}\text{Cr}$  value of every R chondrite can  
396 represent its bulk parent body.

#### 397 **4.4 Chromium isotope composition of the R chondrite-like clast of** 398 **Almahata Sitta**

399 Almahata Sitta (debris from asteroid 2008 TC3) is a polymict ureilite that  
400 contains not only ureilitic clasts but also some chondritic clasts from OCs and ECs  
401 (Bischoff et al., 2010). One of the chondritic clasts, MS-CH, is unusual. It is a  
402 petrologic type ~3.8 chondrite with a chondrule/matrix ratio of about 1.5. This clast  
403 has a  $\Delta^{17}\text{O} = \sim 1.76$  and contains chondrules with an average size of roughly 450  $\mu\text{m}$

404 (Horstmann et al., 2010). All these characteristics are similar to those of the R  
405 chondrites. The  $^{55}\text{Mn}/^{52}\text{Cr}$ ,  $\epsilon^{53}\text{Cr}$  and  $\epsilon^{54}\text{Cr}$  values for this clast determined here are  
406  $0.70 \pm 0.04$ ,  $0.18 \pm 0.04$ , and  $-0.16 \pm 0.07$ , respectively, and also resemble those of R  
407 chondrites [ $^{55}\text{Mn}/^{52}\text{Cr} = 0.68 \pm 0.04$ ,  $\epsilon^{53}\text{Cr} = 0.23 \pm 0.05$ , and  $\epsilon^{54}\text{Cr} = -0.06 \pm 0.08$   
408 (2SD, N = 12)]. These compositions also support the classification of this clast as R  
409 chondrite-like. It should be noted that this clast cannot have any genetic relationship  
410 to CK chondrites, which have higher  $\epsilon^{54}\text{Cr}$  ranging from  $0.33 \pm 0.12$  (Qin et al., 2010)  
411 to  $0.63 \pm 0.09$  (Trinquier et al., 2007), although the clast contains equilibrated and  
412 metamorphosed olivine, similar to CK chondrites (Horstmann et al., 2010). The  $\delta^{53}\text{Cr}$   
413 value of this clast ( $-0.11 \pm 0.15$ ) is also consistent with that of R chondrites, but since  
414 all chondrites have similar stable isotopic composition, this is not surprising. However,  
415 it should be noted that both the  $\Delta^{17}\text{O}$  and  $\epsilon^{54}\text{Cr}$  values for this clast are slightly lower  
416 than those of the R chondrite group. More importantly, the clast contains some metals  
417 (unknown from R chondrites) and chromites in this clast have much lower  $\text{TiO}_2$   
418 ( $\sim 1.35$  wt.%) contents (Horstmann et al., 2010) than those of R chondrites  
419 (typically  $>5$  wt.%; (Bischoff et al., 2011). There are also no magnetites and  
420 platinum-group-element-rich phases in this clast, while this is usually the case for R  
421 chondrites (Horstmann et al., 2010). Therefore, the chemical, petrological and  
422 isotopic features of this clast do not match any currently known chondrite groups and  
423 it should remain an ungrouped non-carbonaceous chondrite. The similar  $\Delta^{17}\text{O}$  and  
424  $\epsilon^{54}\text{Cr}$  signatures between this clast and the R chondrites may suggest they accreted at

425 a similar locations or in a similar environments in the Solar System (e.g., Desch et al.,  
426 2018). Furthermore, the observation of chondritic clasts in **achondrites** (e.g., Zolensky  
427 et al., 1996; Goodrich et al., Bischoff et al., 2006; 2010; Patzek et al., 2018) is  
428 consistent with the extensive **transportation** processes in early Solar System  
429 (Weidenschilling, 1977), which is also supported by the **transportation** of chondrule  
430 precursors (Olsen et al., 2016; Zhu et al., 2019a; Zhu et al., 2020a) and the  
431 observation of **an** angrite-like clast in a CH chondrite (Zhang et al., 2020).

432

## 433 5. Conclusion

434 This work reports the first high-precision nucleosynthetic signatures of the  
435 Rumuruti (R) chondrites. All the R chondrites possess homogeneous  $\epsilon^{54}\text{Cr}$ :  $-0.06 \pm$   
436  $0.08$  (2SD,  $N = 12$ ), which is independent on their petrological types (R3-R6). The  
437  $\epsilon^{54}\text{Cr}$  values for R chondrites are similar to those of enstatite chondrites, the  
438 Earth-Moon system, and aubrites.

439 R chondrites have  $^{55}\text{Mn}/^{52}\text{Cr}$  of  $\sim 0.68$  and  $\epsilon^{53}\text{Cr}$  of  $0.23 \pm 0.05$  (2SD,  $N = 12$ ),  
440 which are higher than those of most of other chondrite groups. The variable  $^{55}\text{Mn}/^{52}\text{Cr}$   
441 and  $\epsilon^{53}\text{Cr}$  may be caused by the different abundance of chondrules that experienced  
442 volatile-loss and are, on average, depleted in Mn.

443 All the R chondrites with types of 3-6 (as well as brecciated R chondrites)  
444 possess homogeneous  $\delta^{53}\text{Cr}$  values,  $-0.12 \pm 0.03$  (2SD,  $N = 12$ ). This clearly indicates  
445 that metamorphism on chondrite parent bodies does not fractionate Cr stable isotopes.  
446 Combined with other chondrites, all the chondrites define a homogeneous  $\delta^{53}\text{Cr} =$   
447  $-0.12 \pm 0.04$  (2SD,  $N = 40$ ). The  $\delta^{53}\text{Cr}$  homogeneity between chondrites and Earth  
448 confirms that terrestrial core formation and/or any volatilization did not cause Cr stable  
449 isotope fractionation.

450 Finally, the chondritic clast, MS-CH, within the Almahata Sitta polymict ureilite  
451 has  $\epsilon^{53}\text{Cr} = 0.18 \pm 0.04$ ,  $\epsilon^{54}\text{Cr} = -0.16 \pm 0.07$ , and  $\delta^{53}\text{Cr} = -0.11 \pm 0.05$  reinforcing its  
452 close affinity to R-chondrites, **although other chemical and petrological evidence does**



453 not support it to be a clast from the R chondrite parent body.

454

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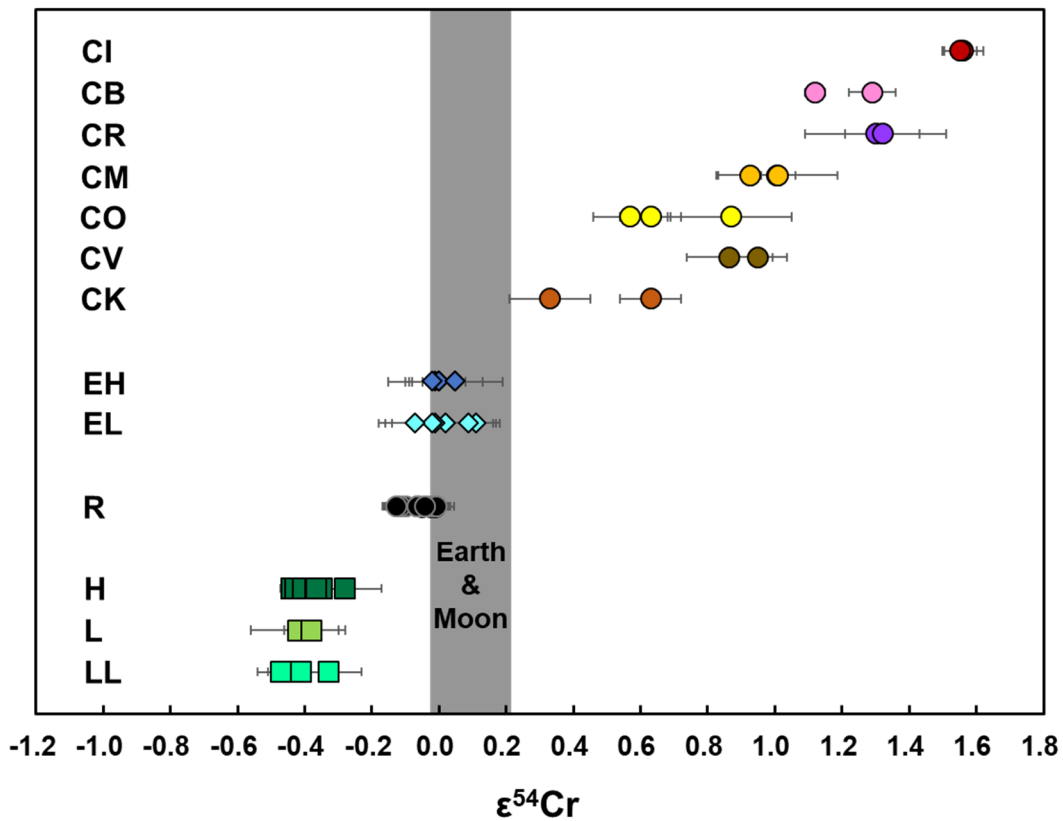
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479 Table 1 The  $^{55}\text{Mn}$ - $^{53}\text{Cr}$  and Cr stable isotope data for Rumuruti (R) chondrites, one R chondrite-like clast in a polymict ureilite (Almahata Sitta)  
 480 and other data quality-control standards.

Name	Type	$^{55}\text{Mn}/^{52}\text{Cr}$	$\epsilon^{53}\text{Cr}$	2SE	$\epsilon^{54}\text{Cr}$	2SE	N	$\delta^{53}\text{Cr}$	2SD	N
Rumuruti	R3.8-6	0.71	<b>0.27</b>	0.03	<b>-0.03</b>	0.04	5	<b>-0.11</b>	0.02	2
PCA 91002	R3.8-6	0.68	<b>0.25</b>	0.01	<b>-0.05</b>	0.07	5	<b>-0.12</b>	0.04	2
LAP 03645	R	0.69	<b>0.20</b>	0.02	<b>-0.01</b>	0.04	5	<b>-0.14</b>	0.02	2
NWA 1476	R3	0.73	<b>0.23</b>	0.02	<b>-0.10</b>	0.06	5	<b>-0.11</b>	0.02	2
NWA 2446	R3	0.60	<b>0.20</b>	0.04	<b>-0.12</b>	0.05	5	<b>-0.11</b>	0.03	2
NWA 753	R3.9	0.66	<b>0.22</b>	0.02	<b>-0.06</b>	0.06	5	<b>-0.09</b>	0.03	2
MIL 07440	R4	0.69	<b>0.25</b>	0.03	<b>-0.06</b>	0.07	5	<b>-0.13</b>	0.04	3
LAP 03639	R4	0.68	<b>0.24</b>	0.01	<b>-0.01</b>	0.06	5	<b>-0.13</b>	0.03	2
NWA 053	R4	0.66	<b>0.27</b>	0.02	<b>-0.13</b>	0.03	5	<b>-0.11</b>	0.03	2
NWA 6145	R5	0.67	<b>0.22</b>	0.02	<b>-0.07</b>	0.10	5	<b>-0.12</b>	0.02	2
MIL 11207	R6	0.69	<b>0.19</b>	0.02	<b>-0.04</b>	0.07	5	<b>-0.12</b>	0.03	2
LAP 04840	R6	0.68	<b>0.22</b>	0.02	<b>-0.03</b>	0.03	5	<b>-0.12</b>	0.02	2
MS-CH	Clast in Ureilite	0.70	<b>0.18</b>	0.04	<b>-0.16</b>	0.07	5	<b>-0.11</b>	0.05	4
BHVO-2	Basalt							<b>-0.11</b>	0.03	2
PCC-1	Peridotite		<b>-0.02</b>	0.03	<b>0.01</b>	0.07	5	<b>-0.08</b>	0.05	4
DTS-2b	Dunite		<b>0.06</b>	0.02	<b>0.12</b>	0.06	5			

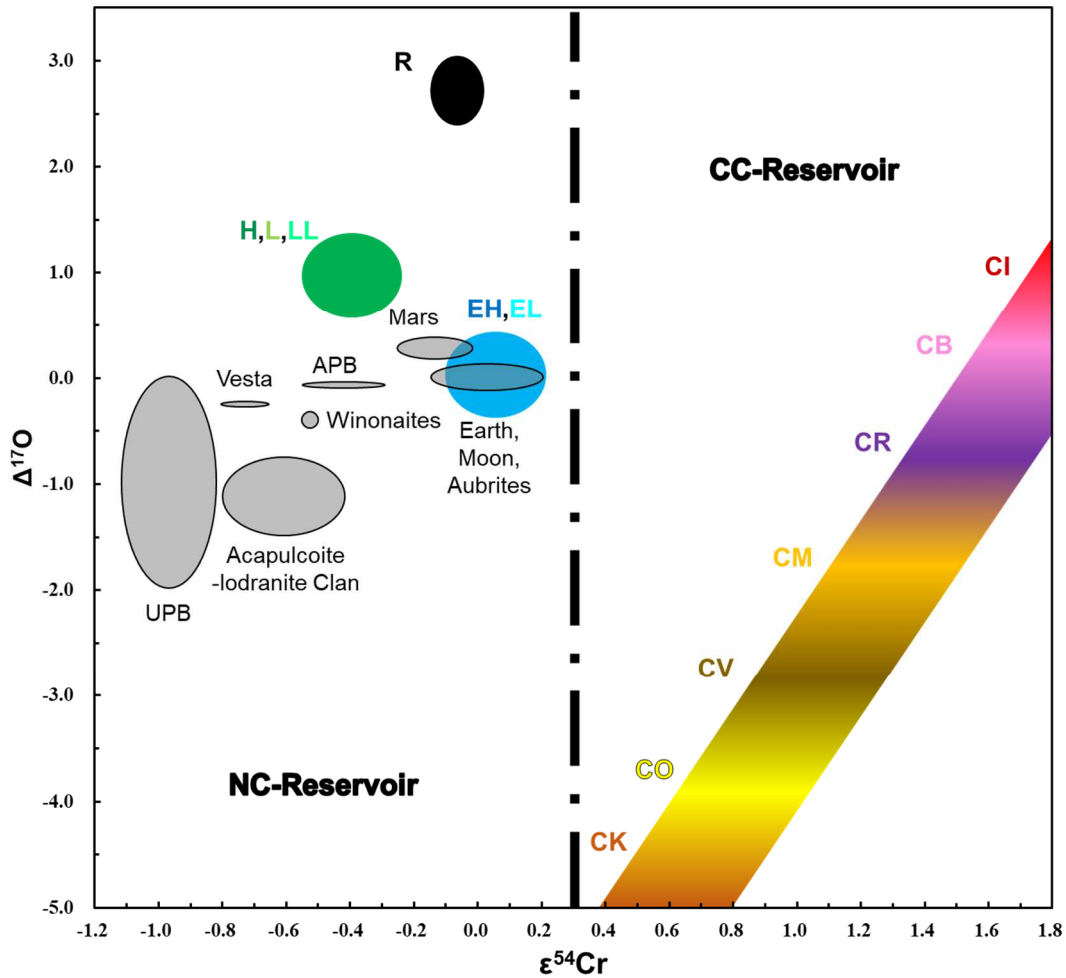
481

### The $\epsilon^{54}\text{Cr}$ Variation in Chondrites



482  
 483 Figure 1 The  $\epsilon^{54}\text{Cr}$  variation for different groups of chondrites. The warm-color circles are the  
 484 carbonaceous chondrites that all possess  $\epsilon^{54}\text{Cr} > 0.3$ , while the blue diamonds, black circles, and  
 485 green squares indicate the enstatite (EH, EL), Rumuruti, and ordinary (H, L, LL) chondrites,  
 486 respectively. The gray bar indicates the  $\epsilon^{54}\text{Cr}$  values for the Earth-Moon system. The data for the  
 487 Rumuruti chondrites are from this study, and the others come from the literature data (Göpel et al.,  
 488 2015; Mougél et al., 2018; Pedersen et al., 2019; Qin et al., 2010; Trinquier et al., 2007; Trinquier  
 489 et al., 2008; Yamashita et al., 2010). The  $\epsilon^{54}\text{Cr} = 0.09 \pm 0.12$  (2SD,  $N = 14$ ) for Earth is from data  
 490 in this study and literature (Mougél et al., 2018; Trinquier et al., 2007), while the  $\epsilon^{54}\text{Cr} = 0.09 \pm$   
 491 0.08 for the Moon is from Mougél et al. (2018).  
 492

The  $\epsilon^{54}\text{Cr}$  vs.  $\Delta^{17}\text{O}$  Diagram for the Solar System Materials

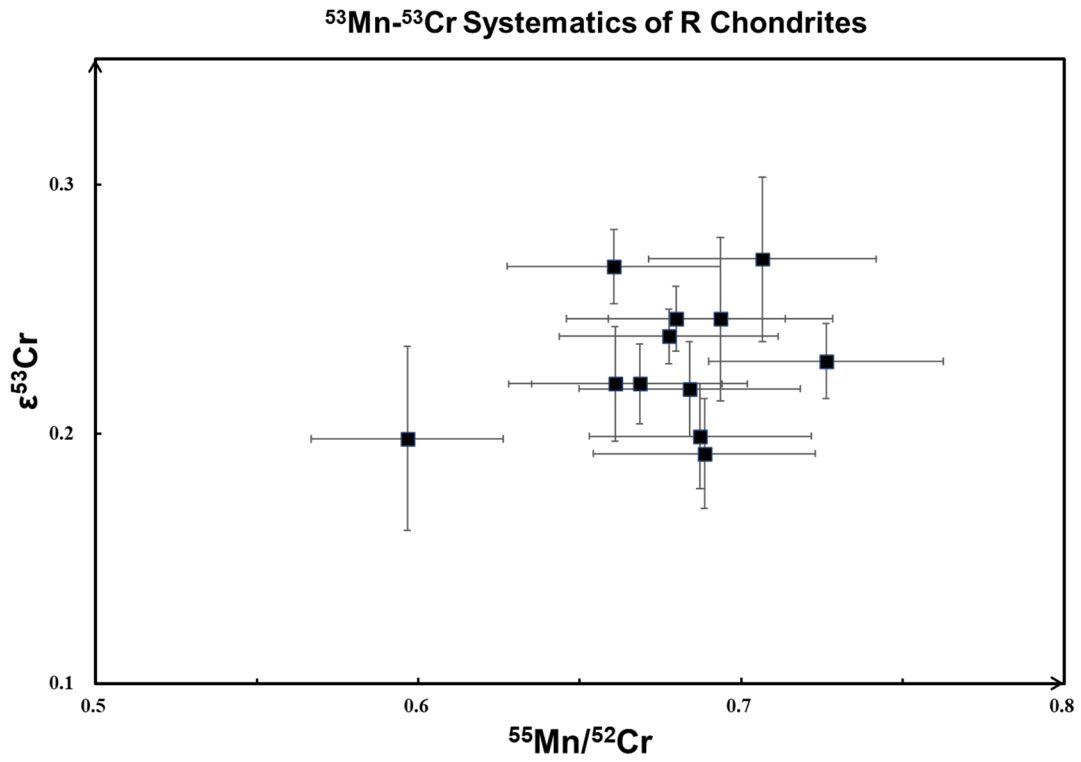


493

494 Figure 2. The  $\epsilon^{54}\text{Cr}$  and  $\Delta^{17}\text{O}$  values of CCs (warm-color shade), OCs (green shade), ECs (blue shade),  
 495 and RCs (black shade), as well as achondrites, terrestrial and lunar samples (gray ellipses). The  $\epsilon^{54}\text{Cr}$   
 496 and  $\Delta^{17}\text{O}$  values are positively correlated in CCs, e.g., CK chondrites have the lowest  $\epsilon^{54}\text{Cr}$  and  $\Delta^{17}\text{O}$   
 497 values, while CI chondrites have the highest  $\epsilon^{54}\text{Cr}$  and  $\Delta^{17}\text{O}$  values (Clayton and Mayeda, 1999;  
 498 Trinquier et al., 2007). The R chondrites (described as average values with 2SD uncertainty) are  
 499 located at the top of this diagram. CC: Carbonaceous chondrite; NC: non-CCs; APB: angrite parent  
 500 body; UPB: ureilite parent body. The colored circles represent the same samples in Fig. 1. The detailed  
 501 data source for Cr isotopes are: chondrites (Göpel et al., 2015; Mougél et al., 2018; Qin et al.,  
 502 2010; Trinquier et al., 2007), Earth (Qin et al., 2010; Trinquier et al., 2007), Moon (Mougél et al.,  
 503 2018), one aubrite (Trinquier et al., 2007), SNC-Mars (Kruijjer et al., 2020), angrite APB (Zhu et al.,  
 504 2019b), HED-Vesta (Trinquier et al., 2007), Acapulcoite-Lodranite clan (Li et al., 2018),  
 505 Winonaites (Li et al., 2018), UPB (Yamakawa et al., 2010; Zhu et al., 2020b). The O isotope data  
 506 sources are from two review papers (Greenwood et al., 2017; Ireland et al., 2020).

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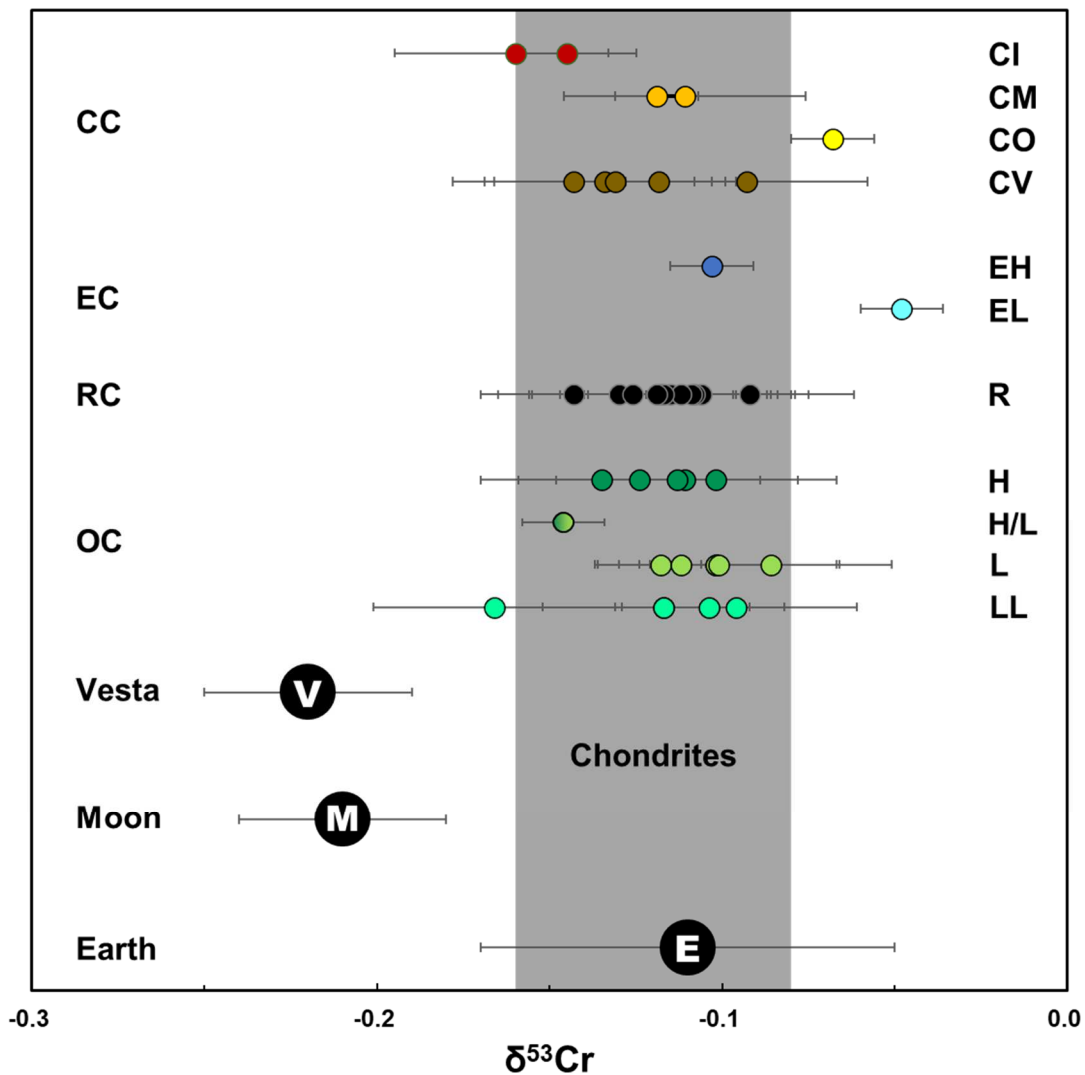


509

510 Figure 3 The  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  data of R chondrites. Most of R chondrite have similar  $^{55}\text{Mn}/^{52}\text{Cr}$  ratios  
 511 ( $\sim 0.68$ ) but distinguishable  $\epsilon^{53}\text{Cr}$  values, which may be caused by the variable abundance of  
 512 chondrules and matrix.

513

## The $\delta^{53}\text{Cr}$ Variation in Chondrites and Planets



514

515 Figure 4. Comparison of the  $\delta^{53}\text{Cr}$  variations amongst chondrites, achondrites and the Earth-Moon  
 516 system. The circles are chondrites of which color corresponds to Figure 1, 2 and 3, while the real  
 517 pictures of planets represent the Earth, Moon and Vesta themselves. The gray bar defines the  
 518 average  $\delta^{53}\text{Cr}$  values ( $-0.12 \pm 0.04$ ; 2SD,  $N = 42$ ) of all the chondrites. Literature data sources:  
 519 chondrites (Bonnand et al., 2016b; Schoenberg et al., 2016), Earth (Jerram et al., 2020;  
 520 Schoenberg et al., 2008; Sossi et al., 2018), Moon (Bonnand et al., 2016a; Sossi et al., 2018) and  
 521 HEDs-Vesta (Zhu et al., 2019c).

522



523 References *Meteoritical Bulletin*.

524 Alexander, C.M.O.D. (2019a) Quantitative models for the elemental and isotopic  
525 fractionations in chondrites: The carbonaceous chondrites. *Geochimica et*  
526 *Cosmochimica Acta* 254, 277-309.

527 Alexander, C.M.O.D. (2019b) Quantitative models for the elemental and isotopic  
528 fractionations in the non-carbonaceous chondrites. *Geochimica et Cosmochimica Acta*  
529 254, 246-276.

530 Allègre, C.J., Poirier, J.-P., Humler, E. and Hofmann, A.W. (1995) The chemical  
531 composition of the Earth. *Earth and Planetary Science Letters* 134, 515-526.

532 Bischoff, A., Geiger, T., Palme, H., Spettel, B., Schultz, L., Scherer, P., Loeken, T.,  
533 Bland, P., Clayton, R. and Mayeda, T. (1994) Acfer 217-A new member of the  
534 Rumuruti chondrite group (R). *Meteoritics* 29, 264-274.

535 Bischoff, A., Horstmann, M., Pack, A., Laubenstein, M. and Haberer, S. (2010)  
536 Asteroid 2008 TC3—Almahata Sitta: A spectacular breccia containing many different  
537 ureilitic and chondritic lithologies. *Meteoritics & Planetary Science* 45, 1638-1656.

538 Bischoff, A., Vogel, N. and Roszjar, J. (2011) The Rumuruti chondrite group.  
539 *Geochemistry* 71, 101-133.

540 Bollard, J., Kawasaki, N., Sakamoto, N., Olsen, M., Itoh, S., Larsen, K., Wielandt, D.,  
541 Schiller, M., Connelly, J.N., Yurimoto, H. and Bizzarro, M. (2019) Combined  
542 U-corrected Pb-Pb dating and <sup>26</sup>Al-<sup>26</sup>Mg systematics of individual chondrules –  
543 Evidence for a reduced initial abundance of <sup>26</sup>Al amongst inner Solar System  
544 chondrules. *Geochimica et Cosmochimica Acta* 260, 62-83.

545 Bonnand, P., Doucelance, R., Boyet, M., Bachèlery, P., Bosq, C., Auclair, D. and  
546 Schiano, P. (2020) The influence of igneous processes on the chromium isotopic  
547 compositions of Ocean Island basalts. *Earth and Planetary Science Letters* 532, 116028.

548 Bonnand, P., Parkinson, I.J. and Anand, M. (2016a) Mass dependent fractionation of  
549 stable chromium isotopes in mare basalts: Implications for the formation and the  
550 differentiation of the Moon. *Geochimica et Cosmochimica Acta* 175, 208-221.

551 Bonnand, P., Williams, H.M., Parkinson, I.J., Wood, B.J. and Halliday, A.N. (2016b)  
552 Stable chromium isotopic composition of meteorites and metal–silicate experiments:  
553 Implications for fractionation during core formation. *Earth and Planetary Science*  
554 *Letters* 435, 14-21.

555 Cano, E.J., Sharp, Z.D. and Shearer, C.K. (2020) Distinct oxygen isotope compositions  
556 of the Earth and Moon. *Nature Geoscience*, 1-5.

557 Clayton, R.N. and Mayeda, T.K. (1996) Oxygen isotope studies of achondrites.  
558 *Geochimica et Cosmochimica Acta* 60, 1999-2017.

559 Clayton, R.N. and Mayeda, T.K. (1999) Oxygen isotope studies of carbonaceous  
560 chondrites. *Geochimica et Cosmochimica Acta* 63, 2089-2104.

561 Dauphas, N. (2017) The isotopic nature of the Earth’s accreting material through time.  
562 *Nature* 541, 521.

563 Dauphas, N., Remusat, L., Chen, J., Roskosz, M., Papanastassiou, D., Stodolna, J.,  
564 Guan, Y., Ma, C. and Eiler, J. (2010) Neutron-rich chromium isotope anomalies in

565 supernova nanoparticles. *The Astrophysical Journal* 720, 1577.

566 Desch, S.J., Kalyaan, A. and Alexander, C.M.D. (2018) The effect of Jupiter's  
567 formation on the distribution of refractory elements and inclusions in meteorites. *The*  
568 *Astrophysical Journal Supplement Series* 238, 11.

569 Göpel, C., Birck, J.-L., Galy, A., Barrat, J.-A. and Zanda, B. (2015) Mn–Cr systematics  
570 in primitive meteorites: Insights from mineral separation and partial dissolution.  
571 *Geochimica et Cosmochimica Acta* 156, 1-24.

572 Greenwood, R.C., Barrat, J.-A., Miller, M.F., Anand, M., Dauphas, N., Franchi, I.A.,  
573 Sillard, P. and Starkey, N.A. (2018) Oxygen isotopic evidence for accretion of Earth's  
574 water before a high-energy Moon-forming giant impact. *Science advances* 4, eaao5928.

575 Greenwood, R.C., Burbine, T.H., Miller, M.F. and Franchi, I.A. (2017) Melting and  
576 differentiation of early-formed asteroids: The perspective from high precision oxygen  
577 isotope studies. *Chemie der Erde* 77, 1-43.

578 Holden, N.E. (1990) Total half-lives for selected nuclides. *Pure and Applied Chemistry*  
579 62, 941-958.

580 Honda, M. and Imamura, M. (1971) Half-life of Mn 53. *Physical Review C* 4,  
581 1182-1188.

582 Horstmann, M., Bischoff, A., Pack, A. and Laubenstein, M. (2010) Almahata  
583 Sitta—Fragment MS-CH: Characterization of a new chondrite type. *Meteoritics &*  
584 *Planetary Science* 45, 1657-1667.

585 Ireland, T.R., Avila, J., Greenwood, R.C., Hicks, L.J. and Bridges, J.C. (2020) Oxygen  
586 Isotopes and Sampling of the Solar System. *Space Science Reviews* 216, 25.

587 Javoy, M., Kaminski, E., Guyot, F., Andrault, D., Sanloup, C., Moreira, M., Labrosse,  
588 S., Jambon, A., Agrinier, P. and Davaille, A. (2010) The chemical composition of the  
589 Earth: Enstatite chondrite models. *Earth and Planetary Science Letters* 293, 259-268.

590 Jerram, M., Bonnard, P., Kerr, A.C., Nisbet, E.G., Puchtel, I.S. and Halliday, A.N.  
591 (2020) The  $\delta^{53}\text{Cr}$  isotope composition of komatiite flows and implications for the  
592 composition of the bulk silicate Earth. *Chemical Geology* 551, 119761.

593 Kallemeyn, G.W., Rubin, A.E. and Wasson, J.T. (1996) The compositional  
594 classification of chondrites: VII. The R chondrite group. *Geochimica et Cosmochimica*  
595 *Acta* 60, 2243-2256.

596 Krot, A.N., Keil, K., Scott, E.R.D., Goodrich, C.A. and Weisberg, M.K. (2014) 1.1 -  
597 Classification of Meteorites and Their Genetic Relationships A2 - Holland, Heinrich D,  
598 in: Turekian, K.K. (Ed.), *Treatise on Geochemistry (Second Edition)*. Elsevier, Oxford,  
599 pp. 1-63.

600 Kruijer, T.S., Borg, L.E., Wimpenny, J. and Sio, C.K. (2020) Onset of magma ocean  
601 solidification on Mars inferred from Mn-Cr chronometry. *Earth and Planetary Science*  
602 *Letters*, 116315.

603 Larsen, K.K., Trinquier, A., Paton, C., Schiller, M., Wielandt, D., Ivanova, M.A.,  
604 Connelly, J.N., Nordlund, Å., Krot, A.N. and Bizzarro, M. (2011) Evidence for  
605 magnesium isotope heterogeneity in the solar protoplanetary disk. *The Astrophysical*  
606 *Journal Letters* 735, L37.

607 Larsen, K.K., Wielandt, D., Schiller, M. and Bizzarro, M. (2016) Chromatographic  
608 speciation of Cr(III)-species, inter-species equilibrium isotope fractionation and  
609 improved chemical purification strategies for high-precision isotope analysis. *Journal*  
610 *of Chromatography A* 1443, 162-174.

611 Li, S., Yin, Q.-Z., Bao, H., Sanborn, M.E., Irving, A., Ziegler, K., Agee, C., Marti, K.,  
612 Miao, B., Li, X., Li, Y. and Wang, S. (2018) Evidence for a multilayered internal  
613 structure of the chondritic acapulcoite-lodranite parent asteroid. *Geochimica et*  
614 *Cosmochimica Acta* 242, 82-101.

615 Liu, C.Y., Xu, L.J., Liu, C.T., Liu, J., Qin, L.P., Zhang, Z.D., Liu, S.A. and Li, S.G.  
616 (2019) High-Precision Measurement of Stable Cr Isotopes in Geological Reference  
617 Materials by a Double-Spike TIMS Method. *Geostandards and Geoanalytical Research*  
618 43, 647-661.

619 Lugmair, G. and Shukolyukov, A. (1998) Early solar system timescales according to <sup>53</sup>  
620 <sup>Mn-53 Cr</sup> systematics. *Geochimica et Cosmochimica Acta* 62, 2863-2886.

621 Mahan, B., Moynier, F., Siebert, J., Gueguen, B., Agranier, A., Pringle, E.A., Bollard, J.,  
622 Connelly, J.N. and Bizzarro, M. (2018) Volatile element evolution of chondrules  
623 through time. *Proceedings of the National Academy of Sciences*, 201807263.

624 McCammon, C. (2005) The paradox of mantle redox. *Science* 308, 807-808.

625 Mougel, B., Moynier, F. and Göpel, C. (2018) Chromium isotopic homogeneity  
626 between the Moon, the Earth, and enstatite chondrites. *Earth and Planetary Science*  
627 *Letters* 481, 1-8.

628 Moynier, F., Yin, Q.-Z. and Schauble, E. (2011) Isotopic evidence of Cr partitioning  
629 into Earth's core. *Science* 331, 1417-1420.

630 Nittler, L.R., Alexander, C.M.D., Liu, N. and Wang, J. (2018) Extremely <sup>54</sup>Cr-and  
631 <sup>50</sup>Ti-rich Presolar Oxide Grains in a Primitive Meteorite: Formation in Rare Types of  
632 Supernovae and Implications for the Astrophysical Context of Solar System Birth. *The*  
633 *Astrophysical Journal Letters* 856, L24.

634 Nyquist, L., Lindstrom, D., Mittlefehldt, D., SHIH, C.Y., Wiesmann, H., Wentworth, S.  
635 and Martinez, R. (2001) Manganese-chromium formation intervals for chondrules from  
636 the Bishunpur and Chainpur meteorites. *Meteoritics & Planetary Science* 36, 911-938.

637 Olsen, M.B., Wielandt, D., Schiller, M., Van Kooten, E.M.M.E. and Bizzarro, M. (2016)  
638 Magnesium and <sup>54</sup>Cr isotope compositions of carbonaceous chondrite chondrules –  
639 Insights into early disk processes. *Geochimica et Cosmochimica Acta* 191, 118-138.

640 Pack, A. and Herwartz, D. (2014) The triple oxygen isotope composition of the Earth  
641 mantle and understanding  $\Delta O17$  variations in terrestrial rocks and minerals. *Earth and*  
642 *Planetary Science Letters* 390, 138-145.

643 Palme, H., Lodders, K. and Jones, A. (2014) 2.2 - Solar System Abundances of the  
644 Elements, in: Holland, H.D., Turekian, K.K. (Eds.), *Treatise on Geochemistry* (Second  
645 Edition). Elsevier, Oxford, pp. 15-36.

646 Palme, H., Weckwerth, G. and Wolf, D. (1996) The composition of a new R-chondrite  
647 and the classification of chondritic meteorites, *Lunar and Planetary Science*  
648 *Conference*.

649 Pedersen, S.G., Schiller, M., Connelly, J.N. and Bizzarro, M. (2019) Testing accretion  
650 mechanisms of the H chondrite parent body utilizing nucleosynthetic anomalies.  
651 *Meteoritics & Planetary Science* 54, 1215-1227.

652 Pringle, E.A., Moynier, F., Beck, P., Paniello, R. and Hezel, D.C. (2017) The origin of  
653 volatile element depletion in early solar system material: Clues from Zn isotopes in  
654 chondrules. *Earth and Planetary Science Letters* 468, 62-71.

655 Qin, L., Alexander, C.M.O.D., Carlson, R.W., Horan, M.F. and Yokoyama, T. (2010)  
656 Contributors to chromium isotope variation of meteorites. *Geochimica et*  
657 *Cosmochimica Acta* 74, 1122-1145.

658 Qin, L., Nittler, L.R., Alexander, C.M.O.D., Wang, J., Stadermann, F.J. and Carlson,  
659 R.W. (2011) Extreme <sup>54</sup>Cr-rich nano-oxides in the CI chondrite Orgueil – Implication  
660 for a late supernova injection into the solar system. *Geochimica et Cosmochimica Acta*  
661 75, 629-644.

662 Righter, K., Drake, M.J. and Scott, E. (2006) Compositional relationships between  
663 meteorites and terrestrial planets. *Meteorites and the early solar system II* 943, 803-828.

664 Righter, K. and Neff, K. (2007) Temperature and oxygen fugacity constraints on CK  
665 and R chondrites and implications for water and oxidation in the early solar system.  
666 *Polar Science* 1, 25-44.

667 Rubin, A.E., Fegley, B. and Brett, R. (1988) Oxidation state in chondrites, in: Kerridge,  
668 J.F., Matthews, M.S. (Eds.), *Meteorites and the Early Solar System*. University of  
669 Arizona Press, Tucson, Arizona, pp. 488-511.

670 Rubin, A.E. and Kallemeyn, G.W. (1994) Pecora Escarpment 91002: A member of the  
671 new Rumuruti (R) chondrite group. *Meteoritics* 29, 255-264.

672 Russell, S. (1998) A Survey of Calcium-Aluminum-rich Inclusions from R Chondrites:  
673 Implications for Relationships Between Meteorite Groups. *Meteoritics and Planetary*  
674 *Science Supplement* 33, A131.

675 Sanborn, M.E., Wimpenny, J., Williams, C.D., Yamakawa, A., Amelin, Y., Irving, A.J.  
676 and Yin, Q.-Z. (2019) Carbonaceous Achondrites Northwest Africa 6704/6693:  
677 Milestones for Early Solar System Chronology and Genealogy. *Geochimica et*  
678 *Cosmochimica Acta* 245, 577-596.

679 Schiller, M., Van Kooten, E., Holst, J.C., Olsen, M.B. and Bizzarro, M. (2014) Precise  
680 measurement of chromium isotopes by MC-ICPMS. *Journal of analytical atomic*  
681 *spectrometry* 29, 1406-1416.

682 Schoenberg, R., Merdian, A., Holmden, C., Kleinhans, I.C., Haßler, K., Wille, M. and  
683 Reitter, E. (2016) The stable Cr isotopic compositions of chondrites and silicate  
684 planetary reservoirs. *Geochimica et Cosmochimica Acta* 183, 14-30.

685 Schoenberg, R., Zink, S., Staubwasser, M. and Von Blanckenburg, F. (2008) The stable  
686 Cr isotope inventory of solid Earth reservoirs determined by double spike MC-ICP-MS.  
687 *Chemical Geology* 249, 294-306.

688 Schultz, L., Weber, H.W. and Franke, L. (2005) Rumuruti chondrites: Noble gases,  
689 exposure ages, pairing, and parent body history. *Meteoritics & Planetary Science* 40,  
690 557-571.

691 Schulze, H., Bischoff, A., Palme, H., Spettel, B., Dreibus, G. and Otto, J. (1994)  
692 Mineralogy and chemistry of Rumuruti: The first meteorite fall of the new R chondrite  
693 group. *Meteoritics* 29, 275-286.

694 Shen, J., Liu, J., Qin, L., Wang, S.J., Li, S., Xia, J., Ke, S. and Yang, J. (2015)  
695 Chromium isotope signature during continental crust subduction recorded in  
696 metamorphic rocks. *Geochemistry, Geophysics, Geosystems* 16, 3840-3854.

697 Shen, J., Xia, J., Qin, L., Carlson, R.W., Huang, S., Helz, R.T. and Mock, T.D. (2019)  
698 Stable chromium isotope fractionation during magmatic differentiation: Insights from  
699 Hawaiian basalts and implications for planetary redox conditions. *Geochimica et*  
700 *Cosmochimica Acta*.

701 Shima, M. and Honda, M. (1966) Distribution of spallation produced chromium  
702 between alloys in iron meteorites. *Earth and Planetary Science Letters* 1, 65-74.

703 Shukolyukov, A. and Lugmair, G. (2006) Manganese–chromium isotope systematics of  
704 carbonaceous chondrites. *Earth and Planetary Science Letters* 250, 200-213.

705 Sossi, P., Moynier, F. and van Zuilen, K. (2018) Volatile loss following cooling and  
706 accretion of the Moon revealed by chromium isotopes. *Proceedings of the National*  
707 *Academy of Sciences* 115, 10920-10925.

708 Sossi, P.A., Klemme, S., O'Neill, H.S.C., Berndt, J. and Moynier, F. (2019) Evaporation  
709 of moderately volatile elements from silicate melts: experiments and theory.  
710 *Geochimica et Cosmochimica Acta* 260, 204-231.

711 Trinquier, A., Birck, J.-L. and Allègre, C.J. (2006) The nature of the KT impactor. A 54  
712 Cr reappraisal. *Earth and Planetary Science Letters* 241, 780-788.

713 Trinquier, A., Birck, J.-L. and Allègre, C.J. (2007) Widespread <sup>54</sup>Cr heterogeneity in  
714 the inner solar system. *The Astrophysical Journal* 655, 1179-1185.

715 Trinquier, A., Birck, J.L., Allègre, C.J., Göpel, C. and Ulfbeck, D. (2008) <sup>53</sup>Mn–<sup>53</sup>Cr  
716 systematics of the early Solar System revisited. *Geochimica et Cosmochimica Acta* 72,  
717 5146-5163.

718 Trinquier, A., Elliott, T., Ulfbeck, D., Coath, C., Krot, A.N. and Bizzarro, M. (2009)  
719 Origin of Nucleosynthetic Isotope Heterogeneity in the Solar Protoplanetary Disk.  
720 *Science* 324, 374-376.

721 Wang, X., Planavsky, N.J., Reinhard, C.T., Zou, H., Ague, J.J., Wu, Y., Gill, B.C.,  
722 Schwarzenbach, E.M. and Peucker-Ehrenbrink, B. (2016) Chromium isotope  
723 fractionation during subduction-related metamorphism, black shale weathering, and  
724 hydrothermal alteration. *Chemical Geology* 423, 19-33.

725 Warren, P.H. (2011) Stable-isotopic anomalies and the accretionary assemblage of the  
726 Earth and Mars: A subordinate role for carbonaceous chondrites. *Earth and Planetary*  
727 *Science Letters* 311, 93-100.

728 Weisberg, M.K., Prinz, M., Kojima, H., Yanai, K., Clayton, R.N. and Mayeda, T.K.  
729 (1991) The Carlisle Lakes-type chondrites: A new grouplet with high  $\Delta^{17}\text{O}$  and  
730 evidence for nebular oxidation. *Geochimica et Cosmochimica Acta* 55, 2657-2669.

731 Wiechert, U., Halliday, A., Lee, D.-C., Snyder, G., Taylor, L. and Rumble, D. (2001)  
732 Oxygen isotopes and the Moon-forming giant impact. *Science* 294, 345-348.

733 Wu, G., Zhu, J.-M., Wang, X., Johnson, T.M. and Han, G. (2020) High-Sensitivity  
734 Measurement of Cr Isotopes by Double Spike MC-ICP-MS at the 10 ng Level.  
735 Analytical Chemistry 92, 1463-1469.

736 Yamakawa, A., Yamashita, K., Makishima, A. and Nakamura, E. (2010) Chromium  
737 isotope systematics of achondrites: Chronology and isotopic heterogeneity of the inner  
738 solar system bodies. The Astrophysical Journal 720, 150.

739 Yamashita, K., Maruyama, S., Yamakawa, A. and Nakamura, E. (2010)  $^{53}\text{Mn}$ - $^{53}\text{Cr}$   
740 chronometry of CB chondrite: Evidence for uniform distribution of  $^{53}\text{Mn}$  in the early  
741 solar system. The Astrophysical Journal 723, 20.

742 Yin, Q., Jacobsen, B., Moynier, F. and Hutcheon, I.D. (2007) Toward consistent  
743 chronology in the early solar system: high-resolution  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  chronometry for  
744 chondrules. The Astrophysical Journal Letters 662, L43.

745 Yin, Q., Yamashita, K., Yamakawa, A., Tanaka, R., Jacobsen, B., Ebel, D., Hutcheon, I.  
746 and Nakamura, E. (2009)  $^{53}\text{Mn}$ - $^{53}\text{Cr}$  Systematics of Allende Chondrules and epsilon  
747  $^{54}\text{Cr}$ - $\Delta$ 17O Correlation in Bulk Carbonaceous Chondrites, Lunar and  
748 Planetary Science Conference, p. 2006.

749 Young, E.D., Kohl, I.E., Warren, P.H., Rubie, D.C., Jacobson, S.A. and Morbidelli, A.  
750 (2016) Oxygen isotopic evidence for vigorous mixing during the Moon-forming giant  
751 impact. Science 351, 493-496.

752 Zhang, A.-C., Kawasaki, N., Kuroda, M., Li, Y., Wang, H.-P., Bai, X.-N., Sakamoto, N.,  
753 Yin, Q.-Z. and Yurimoto, H. (2020) Unique angrite-like fragments in a CH3 chondrite  
754 reveal a new basaltic planetesimal. Geochimica et Cosmochimica Acta 275, 48-63.

755 Zhu, K., Liu, J., Moynier, F., Qin, L., Alexander, C.M.O.D. and He, Y. (2019a)  
756 Chromium isotopic evidence for an early formation of chondrules from the Ornans CO  
757 chondrite. The Astrophysical Journal 873, 82.

758 Zhu, K., Moynier, F., Barrat, J.-A., Wielandt, D., Larsen, K. and Bizzarro, M. (2019b)  
759 Timing and origin of the angrite parent body inferred from Cr isotopes. The  
760 Astrophysical Journal Letters 877, L13.

761 Zhu, K., Moynier, F., Schiller, M. and Bizzarro, M. (2020a) Dating and tracing the  
762 origin of enstatite chondrite chondrules with Cr isotopes. The Astrophysical Journal  
763 Letters 894, L26.

764 Zhu, K., Moynier, F., Schiller, M., Wielandt, D., Larsen, K., van Kooten, E. and  
765 Bizzarro, M. (2020b) Chromium isotopic constraints on the origin the ureilite parent  
766 body. The Astrophysical Journal 888, 126.

767 Zhu, K., Sossi, P.A., Siebert, J. and Moynier, F. (2019c) Tracking the volatile and  
768 magmatic history of Vesta from chromium stable isotope variations in eucrite and  
769 diogenite meteorites. Geochimica et Cosmochimica Acta 266, 598-610.

770