^{53}Mn-^{53}Cr SYSTEMATICS OF ALLENDE CHONDRULES AND ε^{54}Cr—Δ^{17}O CORRELATION IN BULK CARBONACEOUS CHONDRITES.

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Introduction: We recently suggested [1] that carbonaceous chondrites, as undifferentiated primitive objects in the protoplanetary disk, were accreted very early, within the first 1 Ma at the beginning of the Solar System. We have further suggested that the current ^{53}Mn-^{53}Cr data for bulk carbonaceous chondrites [1,2] imply that chondrules in them must also have formed early, given the logical necessity of forming chondrules first before accreting chondrites (we need "sand grains" first to form the cosmic "sandstone"). This simple temporal relationship is, however, at odds with the currently accepted chondrule ^{26}Al-^{26}Mg and some Pb-Pb ages [e.g., 3,4], which at face value point toward 2-3 Ma younger ages. However, a younger chondrule age poses a serious dynamic problem for the early solar nebula, known as the "storage problem" [5], namely, how could particles of CAI-size float in the protoplanetary disk for over 2-3 Ma until chondrules form, without facing head wind and spiraling into the Sun. Poynting-Robertson drag would efficiently remove the CAI-sized dust particles in the solar nebula in a timescale far less than 2-3 Ma. Therefore the important question to ask is this: Is the current age gap between chondrules and CAIs real? Could it be substantiated by the ^{53}Mn-^{53}Cr chronometer? Like the U-Pb system, the ^{53}Mn-^{53}Cr chronometer is ideally suited to date processes affected by volatile element depletion (Pb, Mn are moderately volatile).

Allende chondrules: Our new result is shown in Fig. 1. Relative to the D'Orbigny age anchor [6,7], the ^{53}Mn-^{53}Cr age of Allende chondrules is 4567.91±0.76 Ma. Relative to the LEW 86010 anchor [7,8], the ^{53}Mn-^{53}Cr age of Allende chondrules is 4567.42±0.83 Ma. Our data do not require chondrules in Allende to have formed 2 Ma after the beginning of the Solar System, as defined by the CAI age of 4567.60±0.36 Ma [e.g. 9]. The new data remove the classic "storage problem".

Bulk Carbonaceous Chondrites: Newly obtained bulk carbonaceous chondrite ^{53}Mn-^{53}Cr data are presented as blue squares in Fig. 2. The slope and intercept are indistinguishable from those of Allende chondrules (Fig. 1), suggesting there is no discernable age gap between the two. The bulk carbonaceous chondrite slope in Fig. 2 translates into an absolute ^{53}Mn-^{53}Cr age of 4567.61±0.67 Ma and 4567.12±0.74 Ma relative to the D'Orbigny and LEW 86010 anchors [6-8], respectively.

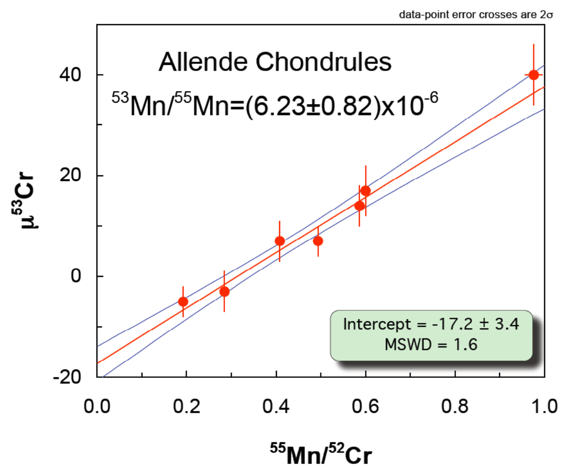

Fig. 1. ^{53}Mn-^{53}Cr isochron for seven Allende chondrules.

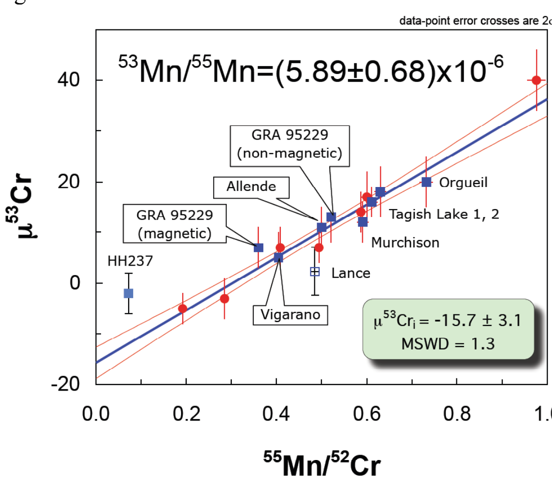

Fig. 2. Bulk carbonaceous chondrites (blue squares) ^{53}Mn-^{53}Cr isochron overlap with Allende chondrules (red circles).

Our data for HH237 (CBb) plot above the bulk carbonaceous chondrite isochron, whereas Lancé (CO3.5) plots below. Lancé may have experienced open system behavior, as it is the highest metamorphic grade sample investigated in this study. HH237 data is inconsistent with that reported for the same meteorite in [2]. The reason for the inconsistency is not clear at this point. Our data suggest HH237 postdates the majority of bulk carbonaceous chondrites by 0.93-4.33 Ma. Its ^{53}Mn-^{53}Cr model age is as young as 4562.9-4563.4 Ma relative to the D'Orbigny and LEW 86010 age anchors [6-8], respectively. This is consistent with the Pb-Pb age of

4562.8±0.9 Ma obtained from the silicate fractions (chondrules) of this meteorite [10].

ε^{54}Cr—Δ^{17}O Correlation in Bulk Carbonaceous Chondrites: Photochemical self-shielding of CO has recently become the most popular model [11-13] to explain the oxygen isotopic anomalies recorded in meteorites. It was originally suggested that these anomalies represent mixing O from stellar nucleosynthetic sources (He burning) with average Galactic chemical composition [14]. One reason to abandon this idea was the lack of observable collateral effects, the expected isotope anomalies in other elements contributed by supernovae [14]. However, there are tantalizing observations that Δ^{17}O is indeed correlated with obvious nuclear anomalies in ^{54}Cr [15,16]. Proponents of the self-shielding model have had reservations about the reality of this correlation for a good reason, namely, the correlation of ε^{54}Cr with O shown by [16] appears much better than is justified by the real data. Admittedly, the average Cr and O isotope compositions reported for a given class of meteorites were not necessarily obtained in the same meteorites [16], notwithstanding that carbonaceous chondrites are notoriously heterogeneous.

Given the significance of any correlation between ε^{54}Cr vs. Δ^{17}O in cosmochemistry and its potential implication, it is imperative to measure Cr and O isotopes in the same suite of samples. Our goal is to provide a consistent set of data without ambiguity, to inform a discussion of the existence of a correlation between ^{54}Cr nuclear anomalies and Δ^{17}O. Fig. 3 shows our new results. We adopted the conventional definition of Δ^{17}O as the vertical deviation of the extraterrestrial materials from the terrestrial fractionation line (TFL). Our results clearly demonstrate a strong correlation between ε^{54}Cr and Δ^{17}O, confirming the observations first noted by [15], and more recently by [16].

Astrophysical models predict that ^{54}Cr along with other neutron-rich isotopes are produced at or near nuclear statistical equilibrium in massive stars prior to their supernova stage [17]. Given the excellent correlation between ε^{54}Cr and Δ^{17}O (Fig. 3), a nucleosynthetic origin for the oxygen isotopic anomalies in the early Solar System may still be viable. It would be surprisingly fortuitous to have photochemical Δ^{17}O anomalies correlated with nucleosynthetic anomalies of ε^{54}Cr. However, the heavier oxygen isotope reservoir (with a ^{54}Cr-rich end member) in Fig. 3 is not the same as the classic ^{16}O-rich, He-burning supernova source originally proposed [14].

A similar trend is observed at the planetary scale (Fig. 4). Planetary differentiation and mixing reduced the isotopic variations but did not erase them. The fact that ε^{54}Cr $\leq$0 for the differentiated objects in Fig. 4, as opposed to the unanimously positive values seen in carbonaceous chondrites (Fig. 3), suggests that nucleosynthetic source(s) contributed ^{54}Cr anomalies to different parts of the solar nebula with pre-existing heterogeneous oxygen isotope reservoirs.

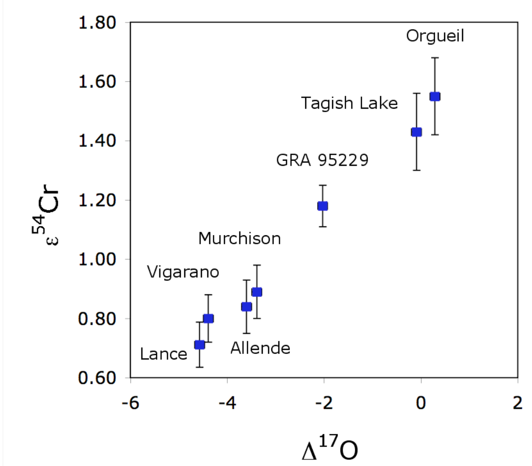

Fig. 3. ε^{54}Cr and Δ^{17}O correlation obtained from the same samples of seven carbonaceous chondrites.

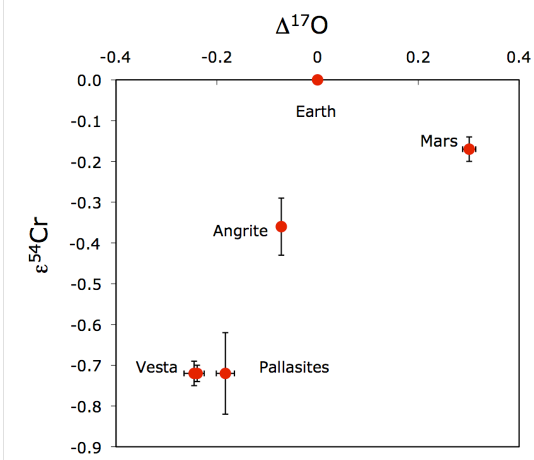

Fig. 4. Planetary scale ε^{54}Cr — Δ^{17}O correlation. Data from [16,18,19]. Note that ε^{54}Cr$\leq$0 compared to Fig. 3.

References: [1] Moynier et al. (2007) *ApJL*, 671, L181. [2] Shukolyukov & Lugmair (2006) *EPSL*, 250, 200. [3] Kurahashi et al. (2008) *GCA*, 72, 3865. [4] Connelly et al. (2008) *ApJL*, 675, L121. [5] Cameron (1995) *Meteorit.*, 30, 133. [6] Glavin et al. (2004) *MAPS*, 39, 693. [7] Amelin (2008) *GCA*, 72, 221. [8] Lugmair & Shukolyukov (1998) *GCA*, 62, 2863. [9] Jacobsen, B. et al. (2008) *EPSL*, 272, 353. [10] Krot et al. (2005) Nature, 436, 989. [11] Clayton, R. (2002) *Nature* 415, 860. [12] Yurimoto & Kuramoto (2004) *Science* 305, 1763. [13] Lyons & Young (2005) *Nature* 435, 317. [14] Clayton, R. (2008) *RMG*, 68, 5. [15] Shukolyukov & Lugmair (2000) *MAPS*, 23, A146. [16] Trinquier et al. (2007) *ApJ,* 655, 1179. [17] Woosley. et al. (2002) *Rev. Mod. Phys.*, 74. 1015. [18] Greenwood et al. (2005) *Nature*, 435, 916. [19] Greenwood et al. (2006) *Science*, 313, 1763.