

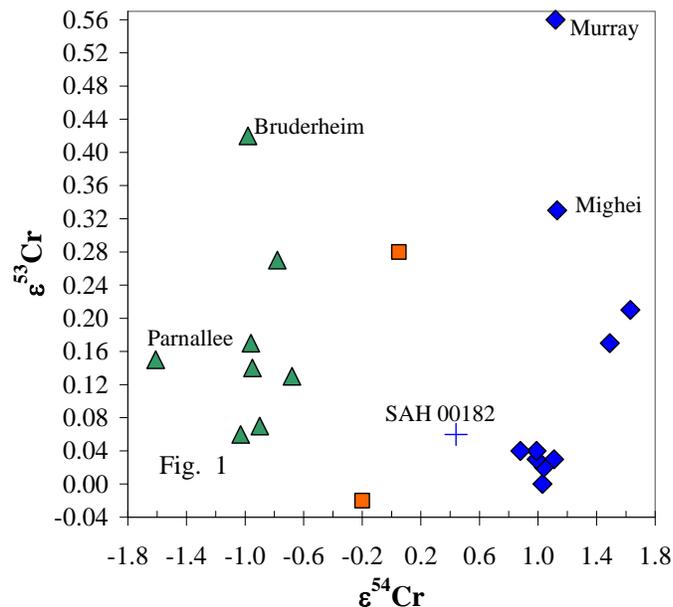
CHROMIUM ISOTOPES IN CHONDRITES AND THE HETEROGENEOUS ACCRETION OF THE SOLAR NEBULA.

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Introduction. The Sun and the solar nebula formed together with other stars from a molecular cloud. The mixing of molecular clouds requires longer times than does star formation, thus it is not surprising that high-precision studies of several elements have shown isotopic heterogeneities in several elements in bulk chondrites. We have completed a high-precision study of Cr isotopes in 11 carbonaceous chondrites, 2 enstatite chondrites and 8 ordinary chondrites. Our results confirm and extend previous studies, particularly those of Trinquier et al. (2007, 2008).

Results. Our results are plotted in Fig. 1; with the exception of Murray and Bruderheim, out range of $\epsilon^{53}\text{Cr}$ values is ~ 0.33 and, with the exception of our Parnallee result, our range in $\epsilon^{54}\text{Cr}$ is ~ 3 . Our results agree well with those of Trinquier et al. [1] and Shulolyukov and Lugmair [2]. Our range in $\epsilon^{54}\text{Cr}$ is slightly larger than that of [1], perhaps because we used a more vigorous dissolution step.

The data are based on the chemical processing of powdered aliquots of the chondrites; in most cases we carried out either duplicate studies of a single filament load or we analyzed separate filament loads. Our errors were mostly relatively small, as documented by the clusters in carbonaceous chondrites (CC) and ordinary chondrites (OC). However, the extreme values observed for Parnallee and Murray data must be treated with caution until replicate studies are carried out. The large spread in the EC (squares) should also be confirmed.



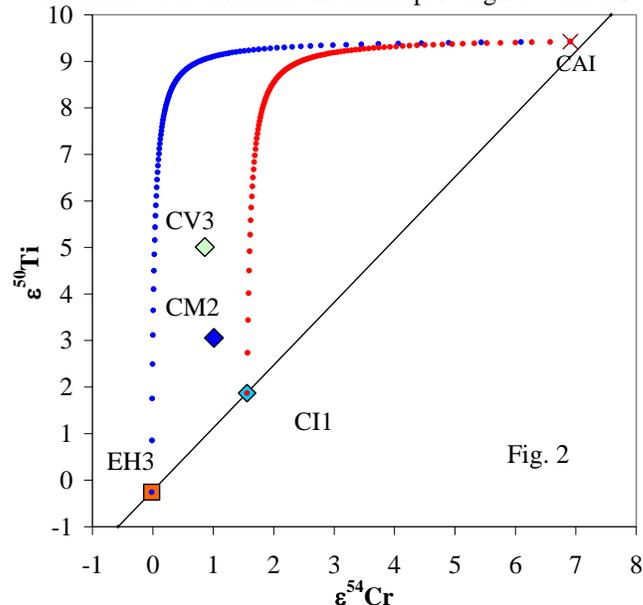
Heterogeneity of the nebula and the molecular cloud.

The most important result from our and previous studies of Cr isotopes is that $\epsilon^{54}\text{Cr}$ values are resolvably different in CC, EC and OC. There is no doubt that the ^{54}Cr anomaly is a nuclear effect and not the product of mass fractionation. This clearly shows that the Cr isotopes were never homogenized' not within the solar nebula nor within the parental molecular cloud. The different classes of chondrites formed from different mixes of the various stellar components that accreted from the molecular cloud to the solar nebula.

This conclusion based on Cr isotopes is supported by other recent studies of isotopes of the nearby elements Ni and Ti [3, 4]. Heavy isotopes anomalies are found in each. However, each isotope has its own story to tell. The preliminary studies to date suggest that several carriers are involved.

An illustration of this is shown in Fig. 2, a type of diagram first used by Trinquier et al. (2009). We plot their $\epsilon^{50}\text{Ti}$ vs. our $\epsilon^{54}\text{Cr}$ values for the four meteorites that we analyzed in common. No OC point is plotted but other data sources show that this would plot just below the EC point on both parameters.

The whole-rock OC, EC and CI chondrites describe a straight line that may be consistent with a single carrier for the anomaly. However, the other CC plot far above this line; Trinquier et al. noted that their positions could be accounted for by mixing Ca-Al-rich inclusions (CAI) materials with chondritic materials plotting between EC



and CI compositions.

We show mixing curves connecting CAI materials with EC and CI positions on the diagram. Although this provides a mechanism for explaining why CV, etc., $\epsilon^{50}\text{Ti}$ values plot above the line, it also shows that one cannot form CI chondrites by adding CAI materials to EC materials and thus demonstrates that the CAIs were not the main carrier of both the Ti and Cr anomalies. It thus demands a minimum of three presolar components in the nebula.

Fig/ 3 shows the strong correlation between the Regelous et al. [3] Ni data and our $\epsilon^{54}\text{Cr}$ results. Although not shown here, the CAI point plots up and to the right of the carbonaceous chondrite points; it plots well off a straight-line fit to the the whole-rock chondrite trend.

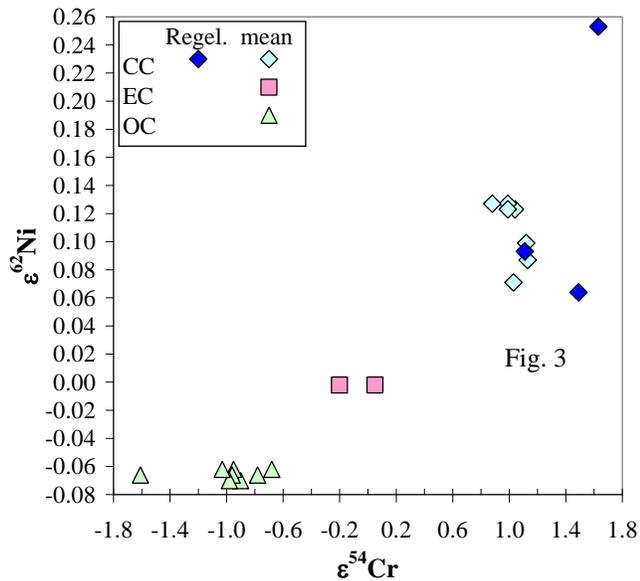


Fig. 3

Refractory inclusions (CAIs) did not form by evaporation of bulk chondrites The common model to account for Ca-Al-rich inclusions is that they formed by evaporation of chondritic materials. Other models attempt to account for them as condensates from a solar-mix of the elements. It is also common to claim that the CI chondrites have the same composition as the Sun (although some recent models now allow the O-isotopes to have been replaced in these by non-mass-dependent processes).

The Cr, Ni and Ti isotopic data are inconsistent with both of these possibilities. The heavy isotope anomalies in CAI are far outside the range observed in whole-rock chondrites, and these anomalies did not form by mass-dependent fractionation. It is thus clear that the anomalies in CAI are not the result of evaporation of these elements from a precursor material; not only can CAI isotopic compositions not be created by evaporating CI

chondrites, they can neither be created by evaporating any of the known chondrite groups nor mixtures of them. This raises the issue of how and where refractory inclusions formed. If they cannot be explained by evaporation or condensation of known materials, is it possible that they are large presolar grains, as was proposed by Wasson (2001)?

Heterogeneity of the presolar molecular cloud. It has been common in the past to assume that the relatively uniform isotopic compositions of the elements in chondrites implied that the parental molecular cloud was well mixed. In fact, it is very difficult to achieve enough turbulence to mix a molecular cloud during its relatively short (10 Ma) lifetime. Even a supernova shock wave should mainly be thought of as a sound wave passing through a medium; some turbulence is certainly introduced, but this has a minor effect on thorough mixing across large distances.

Sequential formation of the chondrite groups? Already the difference in bulk compositions implied that the chondritic groups formed at different locations and/or times. The bulk O-isotopic compositions confirmed the conclusion although schemes involving the large scale transport of O-isotopic anomalies in meter-size icy bodies offered some hope that local compositions could be changed on a relatively short time scale. The bulk chemical anomalies in the iron-group elements now demand separate locations for EC, OC and CC, and may also require separate locations for the various groups of carbonaceous chondrites.

The traditional view has been that all chondrites formed within the Asteroid Belt, either within the inner part (from ~2.0 to ~2.6 AU) or throughout the Belt (out to ~4.0 AU). It is surely correct that the OC formed within the inner belt and that the common groups of CC formed near enough the inner Belt to be close to resonances that would bring them to Earth on a scale of several Ma.

It therefore seems best to conclude that the different clans of chondrites formed sequentially, with some large asteroidal bodies preserving the earlier record.

Summary. The simplest explanation of most isotopic and some chemical variations among the chondrite groups is that these are inherited from the molecular cloud. At least three and probably more presolar components contributed to the chondritic mix. Refractory inclusions may have been one of these presolar components.

References: [1] Trinquier A et al. (2007) *Astrophys. J.* **655**, 1179; [2] Shukolyukov A. and Lugmair G. (2006) *Earth Planet. Sci. Lett.* **250**, 200 [3] Regelous M. et al. (2008) *EPSL* **272**, 330; [4] Trinquier A et al. (2009) *Science*. **324**, 374; [5] Nichols R. et al. (2000) *MaPS* **35**, A119; [6] Wasson J. T. (1999) *MaPS* **34**