Isotopic Diversity Among Meteorites: Implications for the Protoplanetary Disk

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Introduction: Whole rock δ18O and nucleosynthetic isotopic variations for chromium, titanium, nickel, and molybdenum in meteorites define two isotopically distinct populations (Figs. 1-3): carbonaceous chondrites (CCs) and some achondrites, pallasites, and irons in one and all other chondrites and differentiated meteorites in the other [1-5].

Fig. 1. δ18O vs. δ17O for grouped and ungrouped chondrites, differentiated meteorites, and planets. Carbonaceous chondrites and a few differentiated meteorites plot on the right; other chondrites, most differentiated meteorites, the Earth, Mars, and the Moon plot on the left side. The gap between the two populations has scarcely decreased since 2011 [1], even though the number of bodies plotted has increased from 27 to 41. Six Cr data points are from Sanborn & Yin et al. 2006-16 abstracts, which contain other data. See [5] for abbreviations and data sources.

Understanding the distribution of refractory inclusions & elements

Fig. 2. δ13C vs. δ17O for chondrites, differentiated meteorites, and planets. Carbonaceous chondrites and two achondrites, which formed in the outer solar system, are isotopically quite distinct from other chondrites, most differentiated meteorites, and Earth, Mars, and the Moon, which formed in the inner solar system. See [5] for abbreviations and data sources.

Fig. 3. Kruijer et al. [4] δ17O vs. εMa figure showing that carbonaceous chondrites and related iron (CC: blue points) define a separate line from the data for non-carbonaceous (NC) groups including most irons (red points). Ungrouped irons are mostly CC related [2, 36].

Implications: Since the isotopic dichotomy persisted in the disk for >3 Myr from the formation of iron meteorite parent bodies [4, 18] to the formation of CR chondrules [9, 37], it cannot be attributed to temporal variations in the disk. Instead, the two populations (called CC and NC) were most likely separated in space, possibly by proto-Jupiter [4]. Here we discuss implications for understanding CAIs, chondrules, planetesimal accretion, and the formation of the asteroid belt.

Table 1. Inferred accretion times and locations of meteorite parent bodies. Accretion times are inferred from 1-2 Myr ago assuming 16O homogeneity [9, 15, 28]. Mn-Cr dating of secondary phases [16], thermal models for 16O-heatied bodies [17, 28, 44], and H-F core formation ages [4, 18]. Locations refer to currently recognized protective regions (e.g., 4, 5, 6, 9, 32, 36). CC chondrites contain outer SS material [8, 9], but their formation site is unknown [52, 53].

Implications for chondrule formation

The lack of bodies that accreted in the outer solar system between 1 and 2.5 Myr after CAIs suggests that CC chondrites did not accrete until the first generation of planetesimals had melted. This is consistent with chondrule formation by collision of melted planetesimals, although other planetesimal-induced processes may have operated [19].

Did partly differentiated asteroids form with chondritic crusts?

Weiss & Elkins-Tanton et al. [20-23] argue that partly differentiated planetesimals like this schematic CV-CX parent body were common as chromites. However, one may have accreted W and Al or melted and preserved their cool, chondritic crusts. Existence of a core dynamo in the CV body was inferred from the magnetization of the Allende matrix [24]. However, this magnetization may instead result from re-oriented nebular fields [27, 48, 49]. Continued drag-assisted accretion of chondrules could form chondritic crusts [25] but this is incompatible with the absence of mixtures of genetically-related chondritic and differentiated materials in numerous regolith breccias from the surfaces of the parent bodies of howardites, eucrites, and ordinary chondrites [26]. Except possibly for the CB chondrites [28], nearly all chondrites and differentiated meteorites are probably derived from separate bodies.

How did the asteroid belt form?

Three models can account for the origin of CCs and C-type asteroids from beyond Jupiter: Raymond and Izidoro propose that COs and C-type asteroids are scattered into the asteroid belt as Jupiter grows. In their first model, S-type asteroids formed in the inwards migrating Jupiter and Saturn and may explain why C and S types are roughly equally abundant. In their second model, S types are scattered outwards from ~1 AU [30], but Earth and Mercury formed from C-chondrite-like material, not from OCs and S-type asteroids [32, 33]. In the third, preferred Grand Tack model, Jupiter and Saturn migrated inwards, emptying and then repopulating the asteroid belt with roughly equal numbers of planetesimals from inside and outside Jupiter’s orbit [35]. The Grand Tack model accounts for the isotopic dichotomy of meteorites, the mass depletion of the belt, the C/S ratio, and the excited orbits [35]. It should be tested further using isotopic constraints and other meteorite data.