ISOTOPIC DICHOTOMY AMONG METEORITES AND IMPLICATIONS FOR THE EVOLUTION OF THE PROTOPLANETARY DISK.

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Introduction: Whole rock Δ^{17}O and nucleosynthetic isotopic variations for chromium, titanium, nickel, and molybdenum in meteorites define two isotopically distinct populations: 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). Since this dichotomy persisted in the disk for >3 Myr (see below), it cannot be attributed to temporal variations in the disk. Instead, the two populations were most likely separated in space, plausibly by proto-Jupiter [4]. Formation of CCs outside Jupiter helps to explain their characteristic chemical and isotopic composition, the high abundance in comet 81P/Wild 2 of chondrule and CAI fragments [6, 7], and the Mg-Cr and N isotopic evidence that CR chondrites may have formed in the outer solar system [8, 9].

Refractory inclusions and chondrules: The abundance of refractory inclusions in CCs can be explained if they were ejected by disk winds from near the Sun to the disk periphery from where they spiraled inwards due to gas drag [5]. Once proto-Jupiter reached 10–20 $M_\oplus$, it would have accreted gas creating a zone in which the pressure gradient was reversed causing mm- and cm-sized particles to spiral outwards and pile up outside the zone. This scenario would account for the enrichment of CCs in refractory inclusions, refractory elements, and water [10]. Chondrules in CCs show wide ranges in Δ^{17}O as they formed in the presence of abundant ^{16}O-rich refractory grains and ^{16}O-poor ice particles [11]. Chondrules in other chondrites (ordinary, E, R, and K groups) show relatively uniform, near-zero Δ^{17}O as refractory inclusions and ice were much less abundant in the inner solar system [5, 12-14].

Chronology of planetesimal accretion: Accretion times for chondrite parent bodies are best constrained by Hf-W and Al-Mg chondrule ages (assuming ^{26}Al homogeneity) [9, 15], Mn-Cr dating of secondary phases [16], and accretion ages derived from thermal models of bodies heated by ^{26}Al [17]. Inside and outside Jupiter's orbit, chondritic bodies accreted around 2 Myr and 2.5-4 Myr, respectively, after CAIs formed. Accretion times for differentiated parent bodies are 0.4 Myr and ~1 Myr after CAIs for the inner and outer disk respectively, based on thermal models for asteroids and Hf-W segregation ages of irons, which are 0.3-1.8 Myr in the inner solar system and 2.2 to 2.8 Myr in the outer solar system [4, 18]. Earlier accretion times for differentiated planetesimals in the inner solar system are consistent with shorter orbital periods. The absence of bodies that accreted in the outer solar system between 1 and 2.5 Myr after CAIs suggests that CCs 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 also have operated [19].

Can chondrites and differentiated meteorites be derived from the same body? Isotopic similarities between chondrites and differentiated meteorites, the dearth of differentiated asteroids, and thermal models for asteroids have all been used to argue that bodies with chondritic exteriors may contain igneously differentiated interiors [20-23]. The presence of a core dynamo in the CV parent body has been inferred from the magnetic properties of the CV3 chondrite, Allende [24]. Modeling of gas drag-assisted accretion of chondrules onto early accreted asteroids also appears to favor formation of chondritic crusts on differentiated asteroids [25].

However, the widespread chondrite-coated differentiated asteroids are 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, aubrites, ureilites, and E, R, C, and ordinary chondrites [26]. Detailed studies of these breccias show that their components come from very diverse depths. In addition, the Allende magnetic evidence for a CV core needs re-examination as Bland et al. [27] find that impact-generated magnetic fields may be recorded in seemingly low shocked chondrites, and Nagashima et al. [28] infer that the initial concentration of ^{26}Al in the CV body was too low to melt it, assuming rapid accretion. Nearly all chondrites and differentiated meteorites are probably derived from separate parent bodies. CB chondrites may be an exception as they may have accreted from an impact plume on the surface of a differentiated body [29].

Origin of the asteroid belt: Three accretion models for the protoplanetary disk are consistent with the derivation of carbonaceous chondrites from beyond Jupiter, but only the third one appears plausible. 1) Raymond & Izidora [30] proposed that all asteroids formed outside the belt: S type asteroids, from which ordinary chondrites are derived [31], were scattered into the belt by protoplanets in the terrestrial planet region while C types, the parents of CCs [31], were scattered inwards during the growth of Jupiter. However, this model is inconsistent with the isotopic evidence that the Earth formed from material resembling E-chondrites, not from ordinary chondrites [32]. The chemical composition of Mercury suggests that it also formed from E chondrite-like material [33]. 2) The second model envisages that S types formed in the belt and that C types were scattered into the belt by Jupiter as it grew [34]. However, this model cannot easily explain the roughly equal mass of C types and S types (neglecting Ceres) in the belt. 3) In the third model called Grand Tack [35], S types also formed in the belt but they were all removed when Jupiter migrated inwards. The asteroid belt was then repopulated with S and C types when Jupiter tacked outwards. The Grand Tack model can therefore account for the isotopic dichotomy of meteorites, the mass depletion of the belt, the roughly equal proportions of S and C types, and their excited orbits [35].

The idea that chondrites and differentiated meteorites both formed on either side of Jupiter and that they were mixed together when Jupiter migrated across the asteroid belt is a radical new concept that can be readily tested with many kinds of meteorite, asteroid, and theoretical studies.

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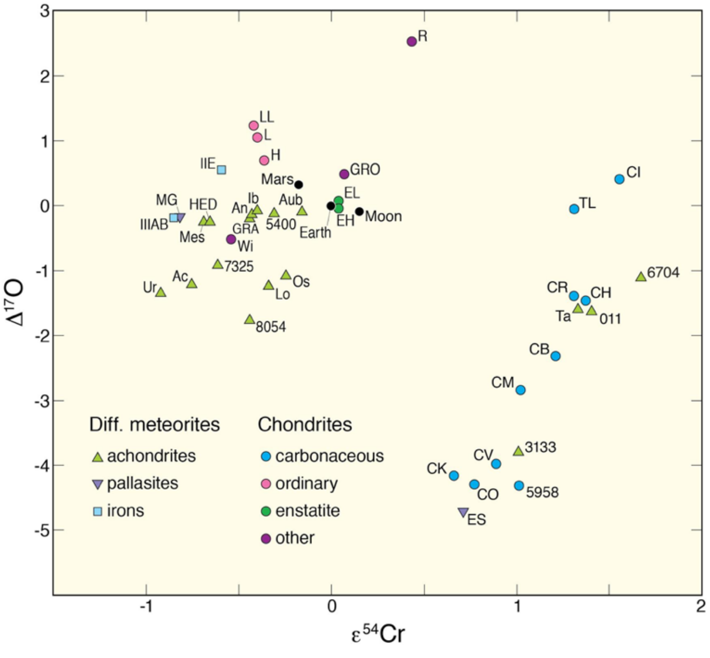

Fig. 1. Plot of the mass-independent isotopic parameters $\Delta^{17}O$ vs. $\varepsilon^{54}Cr$ for chondrites, differentiated meteorites, and planets showing that they are derived from two very distinct isotopic reservoirs. Carbonaceous chondrites and a few differentiated meteorites plot on the right; other chondrites and most differentiated meteorites, the Earth, Mars, and the Moon plot on the left side. The "Warren gap" between the two populations has scarcely decreased since 2011 [1], even though the number of bodies plotted has increased from 27 to 41. $\varepsilon^{54}Cr$ is the deviation of $^{54}Cr/^{52}Cr$ in parts per 10^4 from terrestrial Cr. $\Delta^{17}O = \delta^{17}O - 0.52\delta^{18}O$. For abbreviations and data sources see [5].