NEBULAR HISTORY OF DIFFERENTIATED AND CHONDRITIC PLANETESIMALS

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Introduction: Whole rock $\Delta^{17}O$ values and nucleosynthetic isotopic variations in meteorites provide a new window into the origin of planetesimals and planets. Isotopic compositions of O, Cr, Ti, Ni, and Mo, define two populations: carbonaceous chondrites and a few differentiated meteorites in one (called CC), and all other meteorites and inner solar system bodies in the other (NC) [1–3]. Since the isotopic dichotomy persisted in the disk for >3 Myr, these populations were likely separated by a large protoplanet, probably Jupiter [2]. This division explains the curiously wide range of $^{15}N/^{14}N$ ratios in irons [4]. CC irons have $\delta^{15}N$ values between +3 and +150‰. Group IIC irons have the highest $\delta^{15}N$ values like those in CR chondrites, which are thought to have formed furthest from the Sun [5]. NC irons have lower $\delta^{15}N$ values of –90 to –3‰ [4]. The trend of increasing $\delta^{15}N$ in irons with increasing heliocentric formation distance is consistent with that observed in the solar wind, terrestrial planets, and comets [6, 7]. This supports the contention that isotopic data for meteorites can be used to constrain their formation locations [2].

Planetesimal accretion ages: Hf-W core formation ages are 0.3–1.8 Myr after CAIs in the inner solar system and 2.2–2.8 Myr in the outer region [2]. Thermal models based on these ages assuming ^{26}Al homogeneity in the protoplanetary disk at the canonical level give accretion times for differentiated planetesimals of ≤0.4 Myr and ~0.9 Myr in the inner and outer regions, respectively [2]. In contrast, Al-Mg and Hf-W isotopic ages for chondrules [7–9] and thermal models constrained by peak temperature estimates [26] provide accretion times for chondritic planetesimals of ~2 Myr in the inner solar system and 2.2 to 3.6 Myr in the outer region. Assuming that protoplanets in the inner as well as the outer solar system formed in ≤1 Myr after CAIs, chondritic planetesimals, which formed 2–4 Myr after CAIs, were not the primary building blocks for planets. Chondrules formed throughout the disk (at 1–10 AU) by various planetesimal-induced processes, including bow-shocks [10] and planetesimal collisions [11–13].

Asteroid belt formation models: Four different origins have been proposed for C- and S-type asteroids, which dominate the main belt. 1) C and S types formed in the belt and most of the mass was lost by protoplanetary scattering [14]. 2) Neither C nor S type asteroids formed in the belt: they were scattered in by giant and terrestrial protoplanets, respectively [15]. 3) C asteroids were scattered inwards by Jupiter but S types formed in the belt [16]. 4) The belt was emptied of S asteroids when Jupiter and Saturn migrated inwards and was then repopulated with S types and by C types from beyond Jupiter when the giant planets migrated outwards [17]. The fourth model, called Grand Tack, is the only one that fits the isotopic constraints and provides approximately equal masses of C and S asteroids [18], but a small fraction of C types may have been scattered into the belt during Jupiter’s growth [16].

Origin of differentiated asteroids and meteorites: The IAB irons and aubrites, which have Earth-like isotopic compositions probably formed at ≤1 AU [19, 20] and were scattered into the belt by protoplanets over several Myr [21–23]. However, other large groups of irons, like IIAB, IIIAB, and IVA, and main group pallasites have isotopic compositions that are broadly comparable to those of OCs and probably formed in the belt along with S types, not near ~1 AU [18]. CC irons, like groups IIC, IID, and IVB, and Eagle Station pallasites were probably scattered inwards from beyond Jupiter, mostly during the Grand Tack. Group IVA and IVB are both strongly depleted in Ge and formed in the NC and CC regions, respectively, showing that volatile loss was unrelated to solar proximity and probably reflects impact volatilization [24, 25]. Most planetesimals that accreted <1.5 Myr after CAIs were probably added to protoplanets (or disrupted to make chondrules). Surviving debris from hit-and-run impacts during protoplanetary growth, which is predominantly metal-rich, is taken as the main source of differentiated meteorites and asteroids [23], but chondritic bodies dominate the asteroids as they probably accreted after protoplanets had grown.

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