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PLANET FORMATION: INSIGHTS FROM ASTEROIDS, COMETS, AND METEORITES.

Edward R. D. Scott[1], **Alexander N. Krot**[1], and **Ian S. Sanders**[2]

[1]Hawai'i Institute of Geophysics & Planetology, University of Hawai'i at Manoa, Honolulu, HI 96822, USA; [2]Dept. Geology, Trinity College, Dublin 2, Ireland

Introduction:

We review insights into the formation of major and minor planets from recent cosmochemical, astronomical, and theoretical studies [1–10].

Isotopic dichotomy:

Whole-rock nucleosynthetic isotopic variations for Cr, Ti, Ni, and Mo in meteorites help to identify genetically related meteorites and define two isotopically distinct populations: carbonaceous chondrites (CCs) and a few achondrites, pallasites, and irons in one and all other chondrites (ordinary (O), Rumuruti-like (R), and enstatite (E)) and differentiated meteorites in the other [1–5; Table 1]. Since the dichotomy persisted in the disk for >3 Myr, it cannot be attributed to temporal variations. Instead, the two reservoirs were most likely separated by proto-Jupiter [4]. Formation of CCs outside Jupiter also helps to explain their characteristic high abundance of CAIs (assuming they were deposited there by disk or X winds [5, 11]), high refractory element contents [5,6], chondrule O-isotope compositions [5], and the spectral dichotomy between C and S type asteroids [9], which are linked to CCs and OCs, respectively [12].

Chronology of planetesimal accretion:

Accretion times for differentiated parent bodies in the inner and outer disk, <0.4 and ~1 Myr after CAIs, respectively, are derived from Hf-W ages of irons, which are 0.5–1.5 Myr inside Jupiter and 2.2 to 2.8 Myr outside [4], and thermal models assuming homogeneous $^{26}Al/^{27}Al$ in the protoplanetary disk at the canonical level $(^{26}Al/^{27}Al)_0$ of 5.25´10^{-5} [13]. Accretion times for chondrite parent bodies in the inner and outer disk, ~2 and ~2.5–4 Myr after CAIs, respectively, are derived from ^{26}Al-^{26}Mg and ^{182}Hf-^{182}W chondrule ages [14, 15], ^{53}Mn-^{53}Cr dating of alteration phases [16], and thermal models [17].

Chondrites are commonly inferred to be planetary building blocks. However, in both the inner [19] and outer solar system [4, 20], protoplanets appear to have predated chondrite parent bodies. Thus differentiated parent bodies may be better analog materials for planets.

Why are asteroids and meteorites predominantly chondritic and not differentiated?

We infer that differentiated asteroids were probably disrupted by hit-and-run collisions when protoplanets accreted; chondrite parent bodies formed later and suffered less disruption [21, 22]. Both types would also have been heavily impacted when the inner and outer solar system reservoirs were mixed together. However, porous chondritic bodies are more resistant to impact disruption than basalt rubble piles [23]. Many meteorite types including CB chondrites [24], ureilites [5], IVA and IVB irons [25, 26], E chondrites [27], and IAB irons [28] preserve records of disruptive impacts ~5 Myr after CAIs when the two isotopic reservoirs were probably intermixed.

Formation of Major and Minor Planets:

Earth.

The nucleosynthetic signatures of Earth and E chondrites and achondrites are strikingly similar for a wide range of elements including Ca, Ti, Cr and Ni, and very close for Mo and Ru [29, 30]. Since the isotopic differences are small for these elements and O compared to the total variation in inner solar system materials, Earth probably formed largely from E chondrite-like materials [30], or, if protoplanets near 1 AU formed in < 1 Myr, materials resembling enstatite achondrites.

Mercury.

Low FeO and high S contents are strong evidence for highly reducing materials on Mercury [31]. Consequently, E and CB chondrites have been considered as possible analogs for Mercury [32]. However, CB chondrites, although possessing high metal contents like Mercury [33], are implausible candidates as they formed very late (5 Myr after CAIs [34]) in the outer solar system. Mercury was almost certainly derived from E chondrite-like or achondrite-like precursor materials [31], and may be a mantle-stripped survivor from multiple hit-and-run collisions [21].

Mars.

Given the large number of meteorite types in the inner solar system reservoir, it is curious that no chondrites or 4.5 Gyr-old achondrites match Mars' inferred isotopic composition. These data suggest that Mars could have formed from roughly equal proportions of ECs and OCs [19, 35] or their differentiated cousins. Thus Mars likely formed from a mixture of the dominant inner solar system materials and is not a protoplanet that formed from a narrow zone in the disk.

Jupiter.

Hf-W data for irons require that the inner and outer solar system reservoirs were separated from before 1 Myr to at least 3.5 Myr after CAI formation, when CR chondrites formed [4, 14]. These constraints exclude Jupiter formation in $<10^4$ years by disk instability but are consistent with multi-stage core accretion [20]. The core grew to ~10 M_E by pebble accretion in <1 Myr after CAI formation until it developed an external pressure bump, which impeded further inward flow of pebbles [36]. Over the next ~2 Myr, the core accreted planetesimal fragments heating the gas envelope and delaying rapid gas accretion [20]. After reaching the critical mass of ~50 M_E, proto-Jupiter rapidly accreted its remaining gas. Meteorite data (above) suggest that Jupiter's core was constructed largely from first generation planetesimals like the parent body of Eagle Station pallasites, which are isotopically linked to CV chondrites (Table 1). For Saturn, the achondrites related to CR chondrites are possible analogs [2, 37].

Comets.

The high abundance of chondrule and CAI fragments in comet 81P/Wild 2 [38] does not require large scale transport of material across the entire disk if C chondrites formed beyond Jupiter [1, 5, 6]. CR chondrites, which have chondrules that match the O-isotope composition of 81P/Wild 2 silicates [39], may have formed beyond Saturn [37].

Asteroids:

Four models (*i*–*iv*) have been proposed to account for the asteroid belt [8]. (*i*) The low initial mass model assumes that accretion was very inefficient in the Mars-asteroid region and that S type asteroids accreted in the belt. C types formed beyond Jupiter and were scattered into the belt when Jupiter (and Saturn) grew rapidly [40]. This model explains the isotopic dichotomy between carbonaceous and other chondrites. However, it does not readily explain the grossly similar abundances of C type and S type asteroids in the belt as these would have been controlled by two very different processes.

(*ii*) In the empty belt version of model *(i)*, S type asteroids were scattered into the belt when the terrestrial planets formed [41]. But E type chondrites and achondrites dominated in the Earth-Mercury zone, not S types.

(*iii*) In the early instability model, the giant planet instability that populated the Jupiter Trojans and outer main belt with P and D type asteroids [42] also depleted the Mars region and the asteroid belt of planetesimals and embryos. This model, however, cannot explain the isotopic dichotomy among meteorites.

(*iv*) In the fourth model called Grand Tack [9, 43], S type asteroids formed in the belt but were all removed when Jupiter opened a gap in the disk and migrated inwards to 1.5–2 AU. When Saturn caught up with Jupiter, it became trapped in the 2:3 resonance causing the gas giants to migrate outwards. The asteroid belt was then re-populated with S and C type asteroids, which formed beyond Jupiter. The Grand Tack model is preferred as it can account for the isotopic dichotomy of meteorites, the compositional dichotomy of S and C type asteroids, mass depletion of the belt, roughly equal proportions of S and C type asteroids, their excited orbits [8], the formation of CB chondrites [24, 34] and the disruption of many meteorite parent bodies ~5 Myr after CAI formation.

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Table 1.

Likely formation locations of meteorite types inferred from isotopic data [1–5, 18]

Meteorite	Inner Solar System		Outer Solar System
Type	**Near-Earth**	**outside Mars**	**beyond Jupiter**
Chondrites	Enstatite: EH & EL	Ordinary: H, L, LL; R	Carbonaceous: CI, CM, CO, CV, CK, CB, CH, CR
Irons	IAB	IIAB, IIE, IIIAB, IVA,	IIC, IID, IIF, IIIF, IVB
Achondrites	Enstatite achond.	HEDs, angrites	NWA 011, CR-related achondrites
Stony irons	Mount Egerton	main group pallasites, mesosiderites	Eagle Station pallasites