Chondrite Chronology, Planetesimal Accretion, and Implications for Water Delivery to Earth

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Two advances in the fields of cosmochemistry and solar system dynamics are raising new questions about the materials from which Earth and the other terrestrial planets were made. One is a change in our understanding of the relative antiquity of differentiated and undifferentiated planetesimals in the early solar system and the other is the recognition that planetesimals were widely scattered as a consequence of giant planet migration. We address the potential implications of these advances here.

High-precision chronometers based on short-lived radionuclides and their decay products (e.g., $^{182}Hf/^{182}W$, $^{26}Al/^{26}Mg$) reveal that bodies that differentiated into a rocky mantle and metallic core formed very rapidly, often with metal-silicate separation ages nearly indistinguishable from calcium-aluminum-rich inclusion (CAI) formation. Similarly, it is now well known that chondrules comprising chondrites formed several million years after CAIs. For example, new Mg isotope data from this lab for CV and LL3 chondrites show a single initial $^{26}Al/^{27}Al$ of 1.25×10^{-5}, corresponding to a crystallization age of 1.5 Myr after closure of the solar system based on $\Delta t = -1/\lambda \ln\left((^{26}Al/^{27}Al) / (^{26}Al/^{27}Al)_{\circ} \right)$. These data and other published data analogous to these in turn are suggesting that chondrites themselves accreted as late as ~ 3 and possibly even 4 Myr post CAI. Ordinary chondrites, representing the inner asteroid belt (S-type asteroids), and carbonaceous chondrites, representative of the central asteroid belt (C-type asteroids), both exhibit late chondrule formation (> 1 Myr). Therefore, the idea that heliocentric gradations in the distribution of asteroid types is the consequence of a sharp gradient in accretion time seems less likely now.

A simple order-of-magnitude calculation suggests that the growth timescale for a planetesimal of radius R, in the absence of gravitational focusing, is given by $\tau \sim \rho R / (\sigma\Omega)$ where ρ is the density of the coagulating planetesimals, σ is the mass surface density of solids and Ω is the Keplerian angular frequency around the sun. This implies a growth timescale for a 10km sized planetesimal at 3 AU of $\tau \sim 1.3\,(a / 3\mathrm{AU})^3\,\mathrm{Myr}$ where we used $\rho \sim 3 g/cm^3$ and assumed a minimum mass solar nebular with a surface density profile $\sigma \propto r^{-1.5}$ (r = heliocentric distance). The scaling with semi-major axis, a, suggests a delayed growth of ~3Mys, as indicated by chondrule chronology data, can be achieved by forming planetesimals at 4AU (i.e., beyond the asteroid belt). Formation *in situ* in the asteroid belt would suggest accretion within ~ 0.4 to 1.5 Myr.

Recent models for giant planet migration allow for populating the asteroid belt and the terrestrial planet region with small bodies from distal regions of the early solar system. We suggest that combining the detailed chronology of chondrites with a better understanding of planetesimal growth timescales can be used to test these models.

Responses of deep-sea carbonate system to carbon reorganization and sea level changes

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It is widely accepted that lower atmospheric CO_2 during glacials is caused by a greater sequestration of carbon in deep oceans. However, specific mechanisms causing such changes remain elusive despite intensive studies in the past decades. Transferring carbon into and out of the deep ocean would inevitably affect deep ocean carbonate chemistry such as deep water carbonate ion concentration and carbon isotopes (*1*). The associated deep ocean carbonate compensation and ocean alkalinity changes serve as important feedbacks to further affect atmospheric CO_2. As a step forward to understand the deep ocean carbonate system, we quantify deep-sea carbonate ion concentration using benthic foraminiferal B/Ca (*2*) and $\delta^{11}B$ (*3*) ratios for a few cores from the equatorial Pacific Ocean at various water depths over the last glacial-interglacial cycle. Combined with carbon isotopes, these results provide insights into the carbon cycle in the atmosphere-ocean-terrestrial biosphere system in the past. We explore responses of deep-sea carbonate chemistry to ocean circulation changes, the carbon reorganization within the ocean, and the shelf-basin carbonate fractionation associated with sea level changes. Our data allow us to evaluate past ocean alkalinity changes and their impacts on atmospheric CO_2. The reconstructed deep-sea carbonate ion also places constraints on what controlled the deep ocean carbonate preservation in the past (*4*).

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