Standard Model and Chronology of the Early Solar System Evolution

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Recipe: grind up all the solid components (rock/iron/ice) in the planets of the Solar System into a fine "dust", add gas components assuming the dust to gas ratio of the Sun, then spread the total mass into an annulus ("minimum mass solar nebula"); start the clock and re-run the "movie" of planet formation, the "standard model" predicts the following evolutionary stages in the disk: (1) Coagulation of dust to km-sized planetesimals (10^2-10^4yr at 1 AU), likely through a mechanism known as Goldreich-Ward gravitational instability (not to be confused with the mechanism of formation of coreless, gas-giant planets by Alan Boss); (2) Rapid "runaway" growth followed by slowed-down "oligarchic" growth phase (limited by depletion of supplies) from planetesimals to planetary embryos (~20 "oligarchs"). Stage 2 takes 10^5-10^6yr at 1AU. As observationally inferred disk depletion timescales are 10^6-10^7 yr, "oligarchic" growth would proceed before the disk gas dissipates; (3) In the late stage, the planetary embryos perturb each other into crossing orbits and suffer giant impacts, eventually leading to full size planets (10^7-10^8 yr).

The goal of early Solar System chronology is to use isotopic records, discerned from meteorites and planetary materials in hand, to test the adequacy of the theories of disk evolution and enhance our understanding of solar system evolution. Isotope geo- and cosmo-chemistry have made significant contributions to this area. Recent progress as well as future avenues to explore will be discussed.

The onset of the orbital crossing at stage 3 is debated. Using core formation as a tool to monitor the rate of late stage accretion, the date by Hf-W constrains the timing of stage 3. Late stage sulfide phase segregation into the core was invoked to explain the "Pb paradox" and inconsistency between U-Pb and Hf-W. However, to account for the elevated U/Pb ratio via Pb partitioning into the core, additional mass added to the core after the last Moon-forming giant impact is trivial (<1%). The U-Pb clock therefore "sees the trees but not forest" of core formation, as the U-Pb record necessarily misses >99% of the core formation processes.

Given the lifetime of a solar nebula is likely <10 Ma, a signficant and interesting challenge is how to form gas giants in the outer disk. Specifically, how to rapidly form massive enough rocky cores of giant planets in order to accrete nebula gas before its dissipation? Isotopic records in meteoritic components have much to offer in shedding light on the problem, in terms of nebular lifetime and redox state changes (via icy body transport across the snowline), and parent body accretion time. These processes are likely very different with or without Jupiter in place. Targeted and concerted efforts by the community may lead to breakthroughs in the near future.