Progress in the early solar system chronology: a sketch of an ever-changing landscape.

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Introduction. The years since the Workshop on the Chronology of Meteorites and the Early Solar System, held on Kauai, Hawai'i, on November 5–7, 2007, are marked with ongoing progress in cosmochronology. Rapid improvements in techniques, discovery of new meteorites unlike any previously known, and findings that what was deemed well established constants are actually variables, will be reflected in an updated review of the solar system chronology we are currently preparing. Along with updating the database of meteorite ages [1], it will involve development of a set of criteria for evaluation of accuracy and consistency of isotopic dates across the entire range of meteorite classes and isotope chronometer systems. Here we present some ideas on what we think is important in meteorite chronology, and invite the cosmochemistry community to discuss them.

Towards reliable isotope chronology. In "terrestrial" geochronology, development of sophisticated ways of extracting simple, closed system parts of crystals, and accurately analyzing them, proved much more productive than analyzing bulk mineral fractions and using elaborate models to interpret their isotopic systems. This trend culminated in establishing EARTHTIME [2] - an organized, community-based international scientific initiative aimed at sequencing Earth history through the integration of high-precision geochronology and quantitative chronostratigraphy. We believe that sequencing the early solar system (ESS) history requires a similar approach. The difference is in much greater diversity of processes in the ESS, and of the isotopic systems used to study them. We need to develop a strategy to deal with this complexity.

What processes are we dating? Isotopic systems measure the timing of the processes that fractionate parent and daughter elements. From this seemingly trivial notion, it follows that some processes can be directly dated, while others cannot. The datable processes include condensation (volatility-induced fractionation), melt crystallization (fractionation driven by crystal-melt partitioning), metasomatism (fractionation driven by solubility in fluids) and silicate-metal separation. The most important processes that can be dated only indirectly through associated chemical fractionations are accretion and planetesimal collisions. Metamorphism can be dated directly if there is a new mineral growth, or complete resetting of isotopic clocks. However, the duration of metamorphic processes is often long compared to the precision of dating, and so the interpretation of the dates relies on the models of cooling and isotopic closure. In comparing isotopic dates of meteorites to each other, it is important to recognize the processes behind these dates, and to remember that different isotopic systems, and different scales of sampling (e.g. whole rock vs. mineral grain vs. ion microprobe or laser ablation spot) can date different processes within the same meteorite. Without identifying these processes, "ages" of meteorites with complex histories can be meaningless.

Which chronometers? Isotopic systems used in meteorite dating can be divided into several groups based on their established usage. Four isotopic systems came to become the main group of modern ESS chronology: $^{207}Pb/^{206}Pb$, ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr, ^{182}Hf-^{182}W. Recent reviews of the ESS chronology [1, 3-6] are based on using these isotopic systems and, considering their wide applicability, we expect to use them as the basis of the upcoming review as well. A wider group of niche chronometers (e.g., ^{10}Be-^{10}B, ^{36}Cl-^{36}S, ^{92}Nb-^{92}Zr, ^{107}Pd-^{107}Ag, ^{146}Sm-^{142}Nd, ^{205}Pb-^{205}Tl, and the systems based on decay of ^{244}Pu) can provide information about the processes that don't fractionate parent / daughter element ratios of the main chronometer group. Some isotopic systems: ^{41}Ca-^{41}K, initial Sr, ^{129}I-^{129}Xe, U-Th-He, appear to be unduly forgotten, despite being very useful in probing timing of vastly different processes. Finally, there is a group of old faithful U-Th-Pb, ^{87}Rb-^{87}Sr, ^{147}Sm-^{143}Nd, ^{40}Ar-^{39}Ar, ^{176}Lu-^{176}Hf chronometers, based on decay of extant radionuclides. These systems usually yield dates that are insufficiently precise for direct use in the ESS chronology, but provide valuable information about possible late disturbances [7,8]. The status of the ^{60}Fe-^{60}Ni system as a chronometer is currently uncertain.

Which meteorites? ESS chronology of the early days was based largely on analysis of the most common and easily available meteorites, such as eucrites and equilibrated ordinary chondrites. Eventually it became clear, however, that the geological histories of these samples were too long and too complex to allow accurate dating precisely linked to the particular processes of ESS evolution.

Modern ESS chronology is based on the studies of three groups of materials: 1) a relatively small number of exceptionally old and well preserved meteorites such as angrites, eucrite-like meteorites of non-HED origin, and some unclassified basaltic achondrites [e.g. 9-11]; 2) chondrules from well-preserved unequilibrated ordinary and carbonaceous chondrites, and 3) calcium-aluminum-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs). Establishing accurate age relationships between these groups of materials is perhaps the most important goal of the ESS chronology. Another equally important task is linking the ages of iron meteorites to the timescale based on the studies of stony meteorites.

Contamination and de-contamination. The detrimental effects of the presence of non-radiogenic counterparts of the daughter isotopes, which must be subtracted in order to calculate the age, are long known in cosmochronology. In order to defeat this problem, researchers are developing sophisticated schemes of acid leaching [12,13]. A troubling finding is that acid leaching may be capable of fractionating radiogenic isotopes of Pb [14]. This means that the leaching and progressive dissolution procedures must be tested for such fractionation. The possibility of age bias is even greater in constructing parent/daughter isochrons: isochrons based on progressive dissolutions have to be verified by analysis of unleached minerals [11].

Half-lives of parent radionuclides. Recently, half-lives were precisely re-determined for four isotopes used in ESS chronology: ^{182}Hf [15], ^{41}Ca [16] ^{60}Fe [17] and ^{146}Sm [18]. The first two papers confirm previously accepted values with greatly improved precision, whereas the latter two suggest drastic revisions. This is a warning against uncritical acceptance of the half-life values. Obtaining reliable half-life values requires a combination of advanced decay counting, careful control of radiochemical purity, and accurate concentration determination with isotope dilution mass spectrometry. Most older half-life studies lack at least one of these components, and their results must be treated with caution.

Initial abundances. The ^{238}U/^{235}U ratio, which was considered constant until recently, is now known to be variable. While variations among the CAIs are most prominent [19], it appears that the ^{238}U/^{235}U ratio in bulk chondrites and achondrites may have only limited variability [10, 20-22]. Revisions of the Pb-isotope chronology of meteorites with consideration of the ^{238}U/^{235}U variability are being undertaken by several research groups [20, 21]. The U isotope ratios of many meteorites precisely dated with the ^{207}Pb/^{206}Pb method are still unknown, and their determination is one of the pressing tasks in refinement of the ESS chronometry.

An intriguing finding is the recent report of mass-independent variations of ^{26}Mg* in materials with near-solar Al/Mg ratios [22], which was interpreted to reflect variations in initial ^{26}Al/^{27}Al among the solar system reservoirs. This important observation needs to be verified by independent analyses of similar or higher precision. Furthermore, similar studies are required for other isotopic systems, especially the main-stream cosmochronometers ^{53}Mn-^{53}Cr and ^{182}Hf-^{182}W.

Data processing artifacts. It was recently discovered that, at low count rates common in SIMS analyses, averaging isotopic ratios can produce a biased value [23]. This implies the need for alternative data processing (averaging counts rather than ratios), and the need to revise previous SIMS measurements, in particular ^{60}Fe-^{60}Ni and ^{53}Mn-^{53}Cr dates.

Standardization becomes more important as precision increases. Several techniques using simultaneous multiple ion beam collection (TIMS, SIMS, ICPMS) achieve or approach ppm level of precision, and claim the same level of accuracy. Standards that work across the entire range of techniques are therefore required.

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