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Early evolution of the solar system: a geochemical perspective

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1 Introduction

Timescales for the earliest processes in the solar system can be inferred from various formation and evolution models of the proto-solar nebula, from theoretical calculations and dynamic simulations, and from observations of circumstellar disks and planets. However precise chronological constraints do not come from models and simulations but are obtained on real objects that experienced these events, hence the interest of meteorites that can be studied in the laboratory. Their geochemical properties and isotopic composition provide various key informations about the accretion, differentiation and early evolution of their parent bodies and about the exact timescales of the processes. To date these events, natural radioactive isotopes are used. While chronometers based on long-lived radionuclides (^{206}Pb-^{207}Pb, ^{147}Sm-^{143}Nd, ^{87}Rb-^{87}Sr) provide absolute ages, extinct radioactivities (^{182}Hf-^{182}W, ^{53}Mn-^{53}Cr, ^{26}Al-^{26}Mg, . . .) only give relative ages but with a high precision (typically better than 0.1 Ma) due to the short half-life of the parent isotope ($t_{1/2} < 100$ Ma). Isotopic systems not only register planetary, but also nebular processes. Isotopes also bring contraints on the stellar environment around the young Sun, on the time interval between the last nucleosynthetic event that delivered matter to the nebula and the formation of the first solid objects in the solar system, on the homogeneity of the solar nebula, and on the possible heat sources at the origin of the melting and differentiation of many planetesimals. In fact, radioactive systems as a whole help constrain the different evolution models of the early solar system because they have at one and the same time different physico-chemical properties and characteristic half-lives that permit to look at different timescales.

2 Results and Discussion

The first objects of the solar system, the refractory inclusions called CAIs, formed in a short time interval of $\sim$0.3 Ma, which gives clues about the thermal evolution of the solar nebula. The formation time of these first condensates 4.56711 Ma ago is considered as the « start » of the solar system. Most magmatic iron meteorites, assumed to represent the metallic core of parent bodies, formed within less than 1.5 Ma of the condensation of CAIs. Some other bodies also differentiated very early : as an example, eucrites (earliest basalts of the solar system) formed by partial melting of an already differentiated parent body less than 4 Ma after the start of the solar system. The amounts of ^{26}Al and ^{60}Fe found in CAIs confirm that these two radionuclides have been the principal heat sources at the origin of planetary melting. Contrary to the scenario accepted until recently, chondrite parent bodies now appear to have accreted later than the parent bodies of iron meteorites, at a time when most ^{26}Al and ^{60}Fe had already decayed. Hence chondrites remained undifferentiated. Recent studies showed however that angrites formed later than eucrites and also later than chondrites. Angrites can be divided into two groups: quenched angrites crystallized $\sim$5 Ma, and slowly cooled angrites $\sim$10 Ma after the start of the solar system. These data, combined with isotopic results obtained on non-magmatic iron meteorites, as well as on metal-rich CB chondrites and on igneous clasts found in some chondrites point toward the key role played by impacts during the first 10-15 Ma of the solar system. The last major impact has been dated at about 50 Ma and is at the origin of the Moon. Isotopes also allow to estimate the mean-life for the accretion of a planet, i.e. the time taken to reach 63% of accretion: a value between 11 and 40 Ma is found for the Earth, depending on the isotopic system considered. Besides, strong constraints can be obtained on core formation in planetary bodies, especially with the ^{182}Hf-^{182}W system.

Isotopes also bring information on the stellar environment around the nascent Sun. The numerous nucleosynthetic isotopic anomalies found in refractory inclusions, in presolar grains, and in special phases carried by chondrites suggest that the matter constituting the solar system results from a mixing between different sources. At the same time evidence exists that some short-lived radionuclides have been produced within the solar system by local irradiation processes during the T-Tauri phase of the early Sun. Finally, it seems that most radionuclides were homogeneously distributed in the early solar system – making the use of radio-chronometers possible – but some short-lived radionuclides were probably (at least partially) heterogeneously distributed, as suggested by ^{53}Cr and ^{60}Ni data. These local, small-scale heterogeneities may help to better understand the dynamics of the nebula.

Recent isotopic data will be presented and the constraints brought by isotope cosmochemistry will be compared with those proposed by models.