The beginning: from dust to planets

Wieler, R.

ETH Zürich, Institute for Isotope Geology and Mineral Resources, Department of Earth Sciences, NO C61, 8092 Zürich

The sun and the planets formed ~4.6 billion years ago from a collapsing fragment of a giant molecular cloud, a huge mass of dust and gas. At the same time, many other stars formed in the same molecular cloud, and probably a sizeable fraction of them became accompanied by planets too. Star and planet formation is a major topic in present-day astrophysics. The Hubble telescope is providing exciting pictures of star forming clouds and protoplanetary disks within them but also of dying stars. These are returning processed matter into the cloud, from where it may get incorporated into freshly born stars and planets.

Meteorites are our best witnesses of the birth and early evolution of our own solar and planetary system. Many of the same processes which can be studied remotely in young stellar systems left traces in meteoritic matter, and meteorites also allow us to shed light on processes which cannot (yet) be studied remotely. As samples from left-over building blocks of planets, meteorites are also crucial for the understanding of the Earth and the other planets.

Fig. 1 shows the carbonaceous chondrite Allende. Chondrites are "cosmic conglomerates", as their constituents accreted from the "solar nebula", the flattened gas and dust disk around the young sun. All chondrites have subsequently been altered within their asteroid-sized parent bodies, but this aqueous or thermal metamorphism was weak enough to leave the original structure more or less intact, allowing us to largely reconstruct the accretionary history. The figure shows the major constituents of chondrites: chondrules, calcium-aluminium-rich inclusions (CAIs) and "matrix" (metallic iron-nickel is hardly discernible in this picture). It is still enigmatic how chondrules formed, but they must have experienced probably multiple melting events. CAIs exclusively consist of minerals with very high melting points such as corundum and spinel. CAIs are thus thought to represent very early condensates from a cooling gaseous "nebula" of solar composition. Matrix partly consists of volatile-rich low-temperature components.

![Figure 1](left): Sub-millimeter sized spheroidal chondrules and irregularly-shaped light calcium-aluminium-rich inclusions (CAIs) of the Allende meteorite. Chondrules and CAIs are embedded in very fine-grained “matrix”. Metallic iron-nickel grains are rare in this meteorite type and hardly discernible here. Width of picture ~2 cm.

![Figure 2](right): A large (~5 μm) presolar graphite grain extracted from the carbonaceous chondrite Murchison.

It has been known since many years that chondrites are the oldest material available on Earth (in macroscopic amounts) and the best samples to determine the age of sun and planets, as well as the timing of a variety of subsequent processes in the early solar system, such as formation and metamorphic history of planetesimals. CAIs and chondrules can now be dated by the Pb-Pb system with a precision of better than 1 Ma. Somewhat surprisingly, CAIs are systematically older than chondrules by 2-3 Ma (e.g. 4567.2±0.6 Ma vs. 4564.7±0.6 Ma). This age difference seems to be real, as it is confirmed by isotope systems involving "short-lived" nuclides (e.g. 26Al, T½ = 0.7 Ma; 53Mn, T½ = 3.7 Ma). Short-lived nuclides do not yield absolute ages, because the radioactive parents are extinct, but the respective daughter nuclides (e.g. 26Mg and 53Cr) allow, in principle, to measure very precise age differences between different early objects. It...
is not easy to explain how CAIs should have been stored in the nebula for ~2-3 Ma before having been incorporated into larger objects, because cm-sized objects in the nebula are expected to spiral into the sun in much shorter times. Perhaps the nebula was very turbulent or CAIs once were parts of larger objects.

Extinct nuclides are also very useful to date later events, e.g., differentiation of planetesimals, core formation of Earth and Mars, the giant Moon-forming impact or the early degassing of Earth. A very powerful nuclide pair to date iron-silicate fractionation is $^{182}$Hf-$^{182}$W (8.9 Ma), because Hf does not enter metal. The mean age of core formation of the Earth is in the range of 30-50 Ma after formation of CAIs, the exact value depending on how well the cores of impacting planetesimals were remixed with the silicate portion of proto-Earth. Planetesimals themselves, represented by certain differentiated meteorites, had separated into core and mantle much earlier, often within a few Ma after CAI formation.

Whether or to what extent ages based on extinct nuclides are meaningful depends on how homogeneous a nuclide was distributed in the solar nebula or portions thereof. This issue is controversial and is closely related to another hotly debated topic: the origin of the short-lived nuclides present in the early solar system. The two contenders are nucleosynthesis in stars as well as to gauge the galactic theories of the formation of the chemical composition of almost all elements in all other terrestrial and extraterrestrial matter demonstrates that the solar nebula has been almost perfectly mixed otherwise.

Presolar grains thus allow us to test and refine theories of the formation of the chemical elements in stars as well as to gauge the galactic chemical evolution, i.e., the change in time and space of abundances of chemical elements in the galaxy. Hence, the study of presolar grains in meteorites is "Astrophysics in the laboratory", perfectly complementing classical astrophysics.

REFERENCES