Meteorites

Window on the early Solar System

from Derek Sears

It is an oft-repeated truism that meteorites are a window on the early Solar System. They are, however, complex: the astronomer B. Pagel once remarked, after taking a cursory glance through the window, that "the oracle is . . . wrapped in obscurity of truly Delphic proportions"[1]. Fortunately, Pagel was unduly pessimistic, because the window sometimes clears to present a unique and fascinating picture of places and processes as they were 4,600 million years ago, as shown in a recent paper by David Wark[2].

One of the most important developments in the study of meteorites over the past few decades is the realization that some meteorites retain a better record of the nebular phase of their history than others; these primitive or type 3 chondrites contain many individual components with particular significance for deciphering the earliest history of solid matter in the Solar System. Some of the better-studied components are the silicate aggregates called chondrules[3]; the fine-grained, almost smoke-like, matrix[4]; certain kinds of metal grain[5]; and the graphite–magnetite aggregates[6]. But the objects which have attracted the most attention are calcium–aluminium-rich inclusions (CAIs)[7], one of which is the subject of Wark's paper.

Wark describes a CAI discovered in the Allende meteorite shortly after it fell in 1969. The inclusion (CAI 3643) consists of a core, mantle and crust. The crust appears to have been formed by rapid episodic condensation and aggregation in a compositionally unchanging gas. The core consists predominantly of hibonite, a mineral which is one of the first to condense in a gas of solar composition, whereas the mantle and crust consist predominantly of melilite, which is thought to form by reaction between the hibonite and the gas. The core has the texture of a material which formed by deposition from a vapour. There are many metal nuggets in the centre of the core which consist of highly refractory trace elements, whereas those in the outer parts of the core contain elements of less refractory nature — it is as if they mopped up the elements missing from the nuggets at the core's centre. Other refractory trace elements, the rare-earth elements, show a steady decrease in abundance with increasing volatility, as if the formation of the CAI occurred over the same temperature interval as the elements were condensing.

All these details are consistent with an episodic condensation and accretion of the core, with the mantle and crust being made by later episodes of condensation onto the earlier-formed solids. The processes occurred at high temperatures and involve solids which are refractory to various degrees. Once formed, the entire assemblage suffered several alteration processes at much lower temperatures, with evidence for metamorphism, metasomatism and the introduction of a vapour rich in halogens, alkali metals and iron.

Many who have worked on this CAI have suggested that the inclusions, or some material in them, were not formed in our Solar System, but were transported here from interstellar space during or just before the formation of the Solar System. This idea is rooted in the unusual isotope ratios frequently encountered in the inclusions. It was long believed that the isotopes in our Solar System became thoroughly mixed during its formation. CAIs also contained several short-lived radioactive isotopes at the time they were formed. Some of the nuclides have very short half-lives (for example ^{26}Al, 0.72 million years), which has suggested[8] that the event which ejected the isotopes into the interstellar medium (say, a supernova explosion) was that which triggered the formation of the Solar System. Thus, the condensation sequences would have occurred in the expanding and cooling shells of ejected supernova material[9].

An alternative view is that interstellar material, with essentially normal chondritic composition, entered the primordial solar nebula at cosmic velocities and became heated in a manner analogous to meteorites entering the atmosphere[10]. The evaporation sequence as the material is heated would be the reverse of the condensation sequence, so that CAIs can be regarded as distillation residues rather than high-temperature condensates[11].

Wark points out that the properties of CAI 3643 are not consistent with ideas that involve exposure to various chemical environments. Although the zones in the inclusion, and the radial gradients in mineralogy and refractory-element chemistry, imply different temperature regimes for the aggregation processes, they must have occurred quickly for the differences to have persisted, and they must have occurred in a gas which did not change very much in its composition. Instead, Wark suggests that the CAI formed in a single place and over a fairly restricted time interval; he favours the formation of the CAI by episodic condensation and aggregation during localized transient heating events in the asteroid belt.

Wark's paper will not lay to rest the idea that CAIs are extra-Solar System in origin. It is always possible, although unlikely, that the various extra-Solar System atmospheres that have been postulated were compositionally very similar and movement from one to another was very rapid. It is also possible that not all CAIs were created in the same way. But Wark provides a clear indication that, in at least this instance, the condensation and accretion sequence was followed episodically and in a very restricted regime of time and environment. In this sense, our window on the early Solar System has cleared a little, and provided us with a view that can be obtained in no other way. □

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