Telltale Inclusions

Mineral grains in the Allende meteorite are studied in order to understand the transition from a cosmic gas cloud to the early solar system

by Lawrence Grossman

Scientists have long recognized that a record of events that occurred at the very beginning of the solar system is preserved in the carbonaceous chondrite meteorites because these objects miraculously escaped later processes, such as vulcanism, that would have erased this information. During the 1960s, the supposition was that these extraterrestrial samples were composed of the very mineral grains that condensed from the solar nebula, the hot gas cloud postulated to have given birth to the sun and the planets. Direct evidence was difficult to obtain, however, as existing specimens of these precious meteorites were considered too small for the extensive studies necessary to test the hypothesis. This barrier was broken suddenly on February 8, 1969, when thousands of pieces of a meteorite fell over a large rural area in the valley of el Rio del Valle de Allende in northern Mexico, providing scientists with four tons of material from a single carbonaceous chondrite. So much material became available that chunks weighing several kilograms were sliced up like loaves of bread. The slicing revealed for the first time that some types of carbonaceous chondrites are heterogeneous mixtures of different types of inclusions, many of which are large enough to be individually sampled and analyzed by several different techniques. I will concentrate here on the wealth of information that was obtained by using these techniques on the coarse-grained, calcium-rich inclusions that constitute about 5 percent of the Allende meteorite.

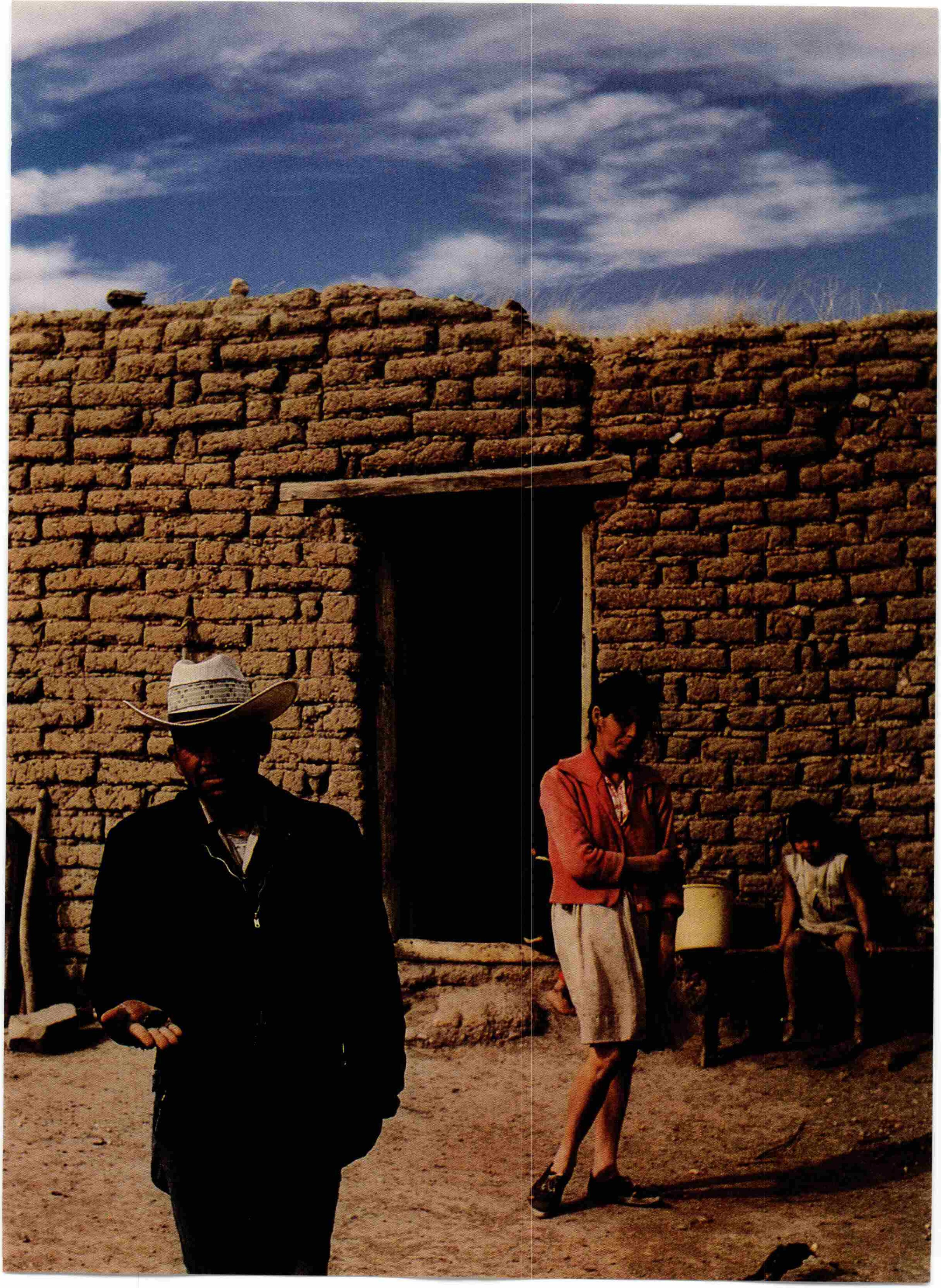
The elements are made in nuclear reactions in the stars. Different elements and different isotopes of the same element are produced in different stars; yet all stable isotopes are found in the solar system. The nuclear products of the stars are ejected into the interstellar medium where they mix together in enormous clouds. In 1969, the prevailing view among cosmochemists was that the solar system formed when such an interstellar cloud of gas and dust underwent gravitational collapse and fragmentation and when one of the fragments continued to collapse into a disk-shaped cloud called the solar nebula. It was thought that during the collapse, gas mixing was thorough enough to erase any preexisting spatial variations in elemental and isotopic composition and that temperatures were high enough in the center of the nebula to evaporate all preexisting interstellar grains. Outer parts of the disk remained cold. The planets in the inner solar system—Mercury, Venus, Earth and its moon, and Mars—were viewed as having accreted from solid materials that condensed in the inner part of the solar nebula when the gas cooled off again. Hence, what minerals condense from a cooling gas of solar composition and in what order are questions of obvious importance to understanding the chemical compositions of the terrestrial planets.

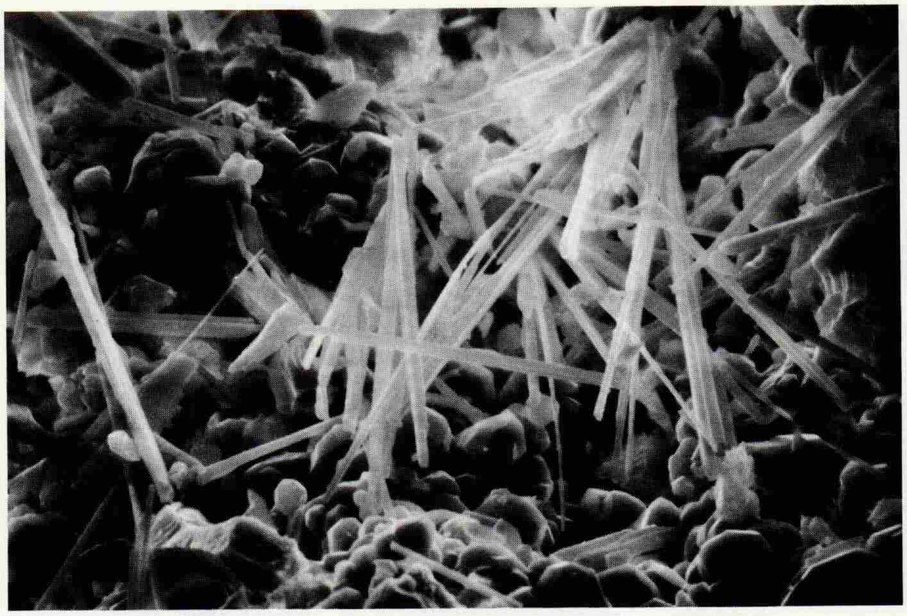
Controlled condensation experiments are difficult to perform at the high temperatures relevant to this problem, but calculations based on the relative stabilities of minerals and gaseous molecules allow detailed predictions that form the basis for discussion of this subject. These models assume that chemical equilibrium was achieved during condensation. (Chemical equilibrium means the tendency of the minerals and gas present at any given time to become as stable as possible.) The models require thermodynamic data for chemical species that can exist in such a system, as well as estimates of the abundances of the elements in the solar system and of pressures and temperatures in the inner solar nebula. Early versions of such calculations predicted that minerals rich in aluminum, calcium, and titanium would be the first-appearing condensates of any of the abundant elements in a cooling gas of solar composition. In 1972, I predicted the sequence in which various minerals would condense under conditions of complete chemical equilibrium.

A slab surface of the Allende meteorite shows that the coarse-grained inclusions are prominent because of their large size and light color. Before long, these objects had attracted the attention of the earliest investigators of the meteorite, who discovered that the white inclusions are filled with calcium-, aluminum-, and titanium-rich minerals. The investigators pro-

A piece of the Allende meteorite is exhibited by its finder on February 16, 1969, eight days after the carbonaceous chondrite fell. This photograph was taken in the town of Torreon de Mata, near the southern end of the large area over which the fragments of the meteorite fell.

Roy S. Clarke, Jr.





I. D. Hutcheon

Two types of coarse-grained inclusions—type A and type B—with different mineralogical compositions have been found in the Allende meteorite. Type A, shown here in a scanning electron micrograph, is irregularly shaped. These inclusions may be aggregates of the original solids that condensed from the solar nebula.

posed, on the basis of this similarity to the minerals that thermodynamic calculations predicted would be the first to condense from a cooling gas of solar composition, that these white inclusions must be high-temperature condensates from the solar nebula.

To study the mineralogy of the inclusions, meteorite pieces containing them are sliced into sections so thin that light passes through. The minerals are then identified by their characteristic colors in a polarizing microscope and analyzed chemically by bombarding the polished surfaces of the sections with electrons. Two kinds of coarse-grained inclusions—type A and type B—with different mineralogical compositions exist. In 1972, I pointed out that, except for one mineral, hibonite, the mineralogical composition of the type A inclusions is precisely the mineral assemblage predicted to be in complete chemical equilibrium with a gas of solar composition in the temperature range 1,175°C to 1,250°C at a total pressure of one-thousandth of an atmosphere, conditions thought to be representative of the inner solar nebula. No thermodynamic data exist for hibonite but it was thought to have condensed first, instead of the mineral corundum predicted by the calculations. Many type A inclusions are irregularly shaped and suggest that, while floating freely in the solar nebula prior to incorporation into the meteorite, they resembled "fluff balls," just what would be expected when small particles strike one another and stick together.

In contrast to fluffy type A inclusions, the type Bs are often nearly spherical, the shape that would be taken by a suspended liquid droplet, and their mineralogical composition is different from the type As. Their coarse crystals are tightly intergrown, a texture typical of materials that crystallized from melts. Some possess outer mantles of the mineral gehlenite, in which it can be shown that the crystals grew from the outer margins of the inclusions inward with falling temperature. This can be readily explained if such inclusions were once molten droplets that cooled and solidified from the outside in by radiating heat away from their surfaces. On the other hand, such inclusions cannot be explained by the condensation of solids from a vapor like the solar nebula, as it is very difficult to see why this would lead to formation of a hollow spherical shell of gehlenite that was filled in by later condensates. Thus, it appears that fluffy type A inclusions could be aggregates of the original solids that condensed from the solar nebula, while many type B inclusions melted either during or after condensation.

Further evidence that both types of coarse-grained inclusions are high-temperature condensates comes from their chemical compositions. Sufficient material can be dug from a single inclusion that it can be analyzed for a large number of elements present in major or trace amounts by a technique known as neutron activation. This technique involves the conversion of stable isotopes into radioactive ones by bombarding the sample with neutrons in a nuclear reactor and then determining the concentrations of elements from the amounts of gamma rays emitted at different energies. Such experiments show that a large number of elements that exhibit a wide range of chemical properties are enriched by the same amount (a factor of 17.5) in the inclusions relative to their abundances in an average sample of solar system matter. Condensation calculations show that the chemically diverse elements analyzed by neutron activation share one characteristic: they all condense from a gas of solar composition above or within the range of condensation temperatures of the major minerals in the inclusions. It must therefore be this common feature that enriched all of these elements to the same degree in the inclusions. Although all refractory elements separated themselves from the rest of solar system matter by forming the inclusions, the fact that the enrichment factors for all these elements are the same indicates that they did not separate from one another in the condensation process.

When viewed in thin section with a polarizing microscope, most inclusions contain dark regions. These areas are filled with many crystals so small that they cannot be resolved under ordinary magnification. This dark material tends to fill veins that cross-cut gehlenite crystals, indicating that it formed after the gehlenite. The same dark material also fills cavities on the edges of the gehlenite crystals, suggesting that the material in the

Type B inclusions, as this example photographed with a light microscope shows, are nearly spherical. Their shape and tightly interlocking grains suggest that they were once molten droplets. The mineral around the edges here is gehlenite. Other smaller inclusions are visible in the surrounding matrix.

R. S. Kjarval

cavities corroded and formed by chemical reaction at the expense of the gehlenite. In order to study the material of the cavities more closely, photographs were taken with a scanning electron microscope and the minerals of that material were identified from the energies of the X-rays emitted by them under electron bombardment. The minerals in the veins and cavities form beautiful, well-developed, multifaced crystals with large amounts of empty space between them. Textures with such empty spaces are usually interpreted as implying crystallization in a gas pocket, a process in which the solid products occupy only a small fraction of the volume of the starting vapor. Although the minerals of these veins and cavities formed by reaction of a previously condensed gehlenite with a gas, none of them are predicted by thermodynamic calculations to condense from a gas of solar composition. One possibility is that the solar nebula differed in chemical composition from place to place and that the Allende inclusions condensed in one region of solar composition but were altered in another area of different composition.

Another indication that the history of the coarse-grained inclusions did not end with the condensation of the major minerals in their interiors is the presence of rim layers around the outsides of these inclusions. Every inclusion is surrounded by the same sequence of four mineralogically distinct rims, each of which is so narrow (three to thirty microns) that a scanning electron microscope is required for its adequate study. The innermost zone is made of typical high-temperature condensates, but the next layer is rich in one of the alteration minerals seen in the veins and that was formed by reaction between the previously condensed minerals and the surrounding nebula. The third layer from the interior of the inclusion consists of another alteration mineral that grades outward in composition to another mineral formed by later condensation. The outermost layer is made of two minerals rich in iron oxide.

The rims have several noteworthy features. Because they are not granular, they cannot have formed by the accretion of grains that crystallized elsewhere, as in sedimentary rocks. Rather, their structure suggests that they crystallized in situ, perhaps by reaction between inclusion interiors and some other material. This reacting material cannot have been minerals in the meteorite matrix in which the inclusions are embedded. The reason is that such a reaction would produce a rim all the way around each inclusion, but sometimes the rims extend only part way around an inclusion even though the matrix completely surrounds the inclusion. Rimming must have occurred prior to the incorporation of the inclusions into the meteorite's parent body, but some rims were broken off between these two events. The rims probably formed in a reaction between the inclusions and the gas of the solar nebula, but some of the reaction products cannot form at chemical equilibrium in a gas of solar composition. Thus, there is once again the possibility that the inclusions were formed in a region of nonsolar composition. The presence of iron oxides in some rim minerals indicates that this region was much more oxidizing than the one from which the interiors of the inclusions condensed because, in it, we know metallic iron was the stable iron-bearing mineral.

In conclusion, we have seen that the Allende meteorite contains objects that crystallized in the cosmic cloud from which the solar system formed. Some are aggregates of mineral grains that condensed directly from the gas of that cloud. These inclusions are our best clues to conditions and processes that occurred in that distant era before the planets formed. Recorded in the inclusions is a rather complex history of successive condensation events and evidence that the cloud was heterogeneous in chemical composition. Data show that the cloud was also isotopically heterogeneous and that collapse of the interstellar cloud to form the solar system may have been triggered by the explosion of a nearby supernova. It seems likely that the inferred spatial heterogeneity of chemical and isotopic composition of the nebula was caused by last-minute injection into the nebula of supernova matter of different composition. Different parts of individual inclusions appear to have reacted with gases of different chemical and isotopic composition, apparently reflecting the fact that the inclusions began forming before newly injected material was thoroughly stirred with the older matter. ☐