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ORIGIN AND EVOLUTION OF ORDINARY CHONDRITE METEORITES,

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About 85% of the meteorites that hit the earth's surface are rocks called chondrites, which are aggregates of materials that formed 4.6 billion years ago from a cloud of dust and gas. These rocks are important for what they can tell us about the origin of the solar system and because they probably resemble the rocks from which the earth formed and its inhabitants evolved. The great majority of chondrites (90%) have very similar chemistry and mineralogy: these 'ordinary' chondrites are pieces of three unidentified asteroids that were removed and transported to earth by collisions among asteroids and comets. Chondrites are named after their major constituent: millimeter-sized spherules called chondrules, which formed from molten droplets in a cloud of dust and gas.

A small fraction of the chondrites (15%) are made of materials that have never been heated above 600°C; these chondrites have been studied intensively for clues to the origin of the solar system. But the great majority of chondrites, including 95% of the ordinary chondrites, are largely made of ingredients that were heated to temperatures between 600 and 900°C. To decipher their history, we need to understand how these rocks were heated inside asteroids and how their mineral textures and compositions were affected. Then we can hope to understand how their ingredients were formed from the primordial cloud of dust and gas - the 'solar nebula'.

Did the baked chondrites form from asteroidal material that resembled the unbaked chondrites? This question has caused much argument among meteorite researchers during the past 20 years because it is not possible to reproduce in the laboratory a process whereby asteroids many miles in diameter were heated for several million years. Differences in the composition and texture of unbaked and baked chondrites are small relative to the range of properties of all meteorites, so that this question cannot be answered without a detailed understanding of chondrite properties and their origins.

A major complication in unravelling the history of the ordinary chondrites and other old planetary materials is that their parent bodies suffered intense bombardment from comets and other asteroids, especially during the first half billion years of their history. This bombardment fractured and mixed the rocks so much that most meteorites are mixtures of materials from various parts of their parent asteroids. About 85% of our samples of asteroids that were once molten are mixtures or 'breccias' of this kind. For the ordinary chondrites it is probable that a similar high proportion are breccias of materials that were baked to various extents. Unfortunately, these breccias are more difficult to identify because the fracturing and mixing process did not greatly change the appearance or composition of chondritic rocks: they were originally diverse mixtures of materials that formed in various parts of the solar nebula. The unbaked and half-baked materials in the chondritic asteroids were easily crumbled and mixed so that only a very small proportion of ordinary chondrites are not breccias of materials with diverse thermal histories. The mixing of material and redistribution of volatile elements during impact heating makes the origin of the ordinary chondrites much more difficult to decipher. Many meteorite researchers have analyzed samples of ordinary chondrites without realizing that they were not studying pure unbaked or baked material. Naturally this has caused much confusion.

Chondrules that were moderately or strongly heated are made of silicate minerals with rather uniform compositions. By contrast, unbaked chondrules are made of silicates with highly variable iron concentrations. Did the heating process homogenize the silicate minerals, or did baked and unbaked chondrules form in different ways in the solar nebula? One group of meteorite researchers has claimed that silicates in baked chondrules have uniform compositions because these chondrules cooled slower in the nebula causing their minerals to homogenize during crystallization. We have found evidence that strongly favors the alternative view that heating in asteroids caused homogenization of mineral compositions.

We have identified one type of chondrule that always contains silicates with low concentrations of iron in chondrites that lack baked material. By studying compositions of silicates in this variety of chondrule in a whole range of chondrites, we have found that the iron concentrations of these silicates vary in a way which is consistent with homogenization during asteroidal heating, and inconsistent with homogenization during crystallization in the nebula. We can make this distinction because the two major silicate minerals in chondrules called olivine and pyroxene tend to crystallize with similar iron concentrations. However, they exchange iron at different rates so that chondrules which contain olivines with high and uniform iron concentrations but pyroxenes with low and variable iron concentrations must have achieved these compositions during heating, not crystallization. Because pyroxenes would take thousands of years to homogenize, it is much more likely that this occurred during slow asteroidal heating, and not during rapid nebular heating.

Subtle differences in the chemical compositions of baked and unbaked ordinary chondritic material have also caused considerable controversy over their origins. Volatile elements are more abundant in unbaked chondrites and they may have been partly lost during slow heating inside asteroids or redistributed during impact heating. However, it is doubtful whether all the chemical differences were caused by heating. Carbon is much more abundant in unbaked than baked chondrites and it is unlikely that loss of carbon monoxide during heating could be the sole cause. We know of some rare baked chondrites that are rich in carbon but we have not identified carbon-poor chondrites composed of unbaked material. If carbon concentrations were controlled by nebular processes, how were nebular and asteroidal processes linked so that all C-poor chondrites were heated in asteroids?

According to the simplest explanation, asteroids were heated by the decay of radioactive atoms such that material at the core was hotter than material at the surface. Carbon and volatile elements condensed from the solar nebula after nebular temperatures had fallen below 300°C. Chondritic material that condensed above this temperature accreted to form the cores of the ordinary chondrite parent asteroids, whereas material that condensed below this temperature accreted on the surface. Thus no C-rich and all C-poor material was baked. There are a number of difficulties with this scheme. Why weren't C-rich and C-poor materials mixed during accretion of planetesimals to make the ordinary chondrite parent bodies? There is evidence for mixing of baked and unbaked material during heating so it would seem to be difficult to preserve chemical differences during accretion. Perhaps the heating source was a hot sun instead of radioactive atoms, or perhaps we misunderstand the chemical changes produced by heating.

Answers to these questions require more detailed laboratory studies of meteorites and the processes which formed them, and exploration of the asteroids themselves. The proposed flyby of asteroid Amphitrite by the Galileo spacecraft in 1986 should show whether the abundant S-type asteroids, such as Amphitrite, are the parent bodies of ordinary chondrites. It will also provide important clues to the nature of impact and heating processes which must have drastically affected most asteroids and planetesimals.