Presolar Grains: Isotopic Clues to Solar System Origin

In retrospect, it should not be surprising to those who study the chemistry of the solar system that its material is inhomogeneous in composition and formed from more than one source. The galaxy is after all a turbulent place, the birth of a star not an event in isolation. But until a few years ago the converse had been widely assumed. The ground rules for interpreting terrestrial, lunar, and meteoritic chemistry included the dictum that processes within the solar system or the solar nebula must explain all observed phenomena.

Recently, however, a growing group of investigators has discovered significant variations in the isotopic composition of meteoritic bodies. As a result of this new evidence, a near-revolution in ideas about the origin of the solar system is taking place. At a recent meeting,* specialists in the subject seemed intrigued and excited by (if not quite ready to adopt) a proposal that up to 2 percent of the atoms heavier than carbon in the solar nebula might have been created in a supernova explosion shortly before the nebula condensed to form planetary bodies. They appeared to accept almost without comment less ambitious models that assume the existence of "presolar" dust grains, of origin unspecified but different from that of the nebular gas cloud, incorporated into accreting planetesimals.

The anomalies discovered so far include variations of up to 5 percent in the isotopic mixture of common elements such as oxygen. Still larger anomalies have been found in rarer elements such as neon, xenon, krypton, and mercury. Smaller anomalies have been reported in magnesium, and the list is still far from complete. As the pattern of isotopic variations becomes clearer, theorists hope it will provide them not only with tracers to identify where in the solar nebula particular bodies were formed, but also with clues to the nucleosynthetic processes by which the particular mix of elements in our solar system was created. Already these newly observed isotopic patterns have narrowed the range of acceptable models for how the moon was made by establishing that it and the earth are geochemically more alike than was once believed.

The earth-moon similarity shows up in data obtained by Robert Clayton and his colleagues at the University of Chicago concerning the relative abundance of oxygen isotopes from those bodies and from meteorites. Meteorites in fact provide the main source of information on average compositions of materials from all over the solar system. Most investigators believe that the many types of meteorites found on the earth provide a representative sample of the solar system's raw materials, and much of the thinking about how planets are formed is based on what is inferred from the meteorites and their properties.

The most primitive type, known as carbonaceous chondrites, show no evidence of heating or melting and are believed to have condensed just as they are from the solar nebula, since their composition resembles that of the sun. The proportion of ^{16}O compared to the other oxygen isotopes in carbonaceous chondrites, however, is anomalously high compared to the mixture found on earth. Clayton explains the difference as due to the mixing of presolar grains of dust containing ^{16}O but almost no ^{17}O or ^{18}O with the solar nebula. Some fragments of these inhomogeneous meteorites contain as much as 5 percent of the ^{16}O-rich materials, while other planetary bodies, such as the earth, contain much less—as little as 0.2 percent. Exactly which minerals or compounds carry the ^{16}O-rich grains has not yet been determined, however.

A complication in interpreting the data is that chemical reactions and physical processes such as evaporation can alter the relative proportions of the isotopes found in samples from a common source—^{16}O evaporates faster than ^{17}O and ^{18}O, for example. These mass fractionation effects are enough to obscure the presence of anomalous material if only two isotopes are measured. Clayton's contribution was to measure all three and observe that values for samples related to each other through mass fractionation would vary in isotopic composition in a systematic way. Thus, data for samples from a single body in the solar system, such as the earth, plotted in terms of these ratios, fall on a single straight line (Fig. 1). Data from a variety of carbonaceous chondrites fall on a completely different line, which Clayton interprets as a mixing line between "ordinary" oxygen and essentially pure ^{16}O, presumably of a different nucleosynthetic origin.

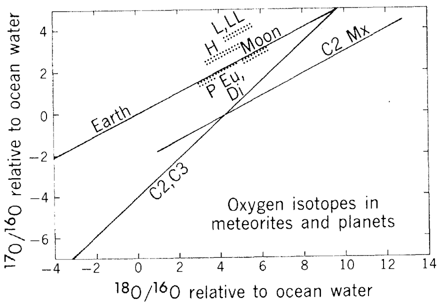

Fig. 1. Oxygen isotopes. L, LL, and H represent data from ordinary chondrites; P, Eu, and Di are achondrites and stony-iron meteorites; C2 and C3 are high-temperature fragments in carbonaceous chondrites; C2 Mx represents low-temperature carbonaceous chondrite materials. [Source: Robert Clayton, University of Chicago]

Other classes of meteorites show still different proportions of anomalous ^{16}O. The largest class, known as ordinary chondrites, show evidence of some heating and metamorphic changes after their formation and are thus considered more highly evolved than the carbonaceous chondrites: they also show the lowest proportion of ^{16}O. Still more highly evolved are meteorites, including a group known as achondrites, which have undergone melting and show evidence of igneous processes similar to those on the earth, and which have an oxygen isotopic composition similar to that of the earth.

The isotopic patterns indicate that the earth was made of matter with a different chemical composition than the chondritic meteorites and could not have been formed from them. The highly evolved meteorites, according to this picture, would be more likely precursor objects. Since the isotopic anomalies presumably reflect inhomogeneities in the solar nebula, these different groups are thought to have originated in different regions of the solar system. Clayton's data indicate that the moon is also a part of the terrestrial group in its isotopic composition. Thus, the isotopic evidence supports models that propose a common origin for the earth-moon system and argues against models that propose capture of a moon originally formed in a different part of the solar system.

A second isotopic anomaly with important geophysical implications occurs in some mineral fragments found in the Al-

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*An all-day session on isotopic variations at a meeting of the American Geophysical Union, 14 April 1976, in Washington, D.C. This article also includes information presented at the AAAS meeting, 23 February 1976, in Boston.

lende meteorite—a body noted for the diversity of materials that it includes. According to Typhoon Lee of the California Institute of Technology, some of the Allende minerals show more ^{26}Mg than would be expected in a normal mixture of magnesium isotopes. The effect is a small one, not larger than 1.3 percent in the samples examined so far, but the amount of the excess appears to be correlated with the amount of aluminum in the mineral. Because of this correlation, many investigators believe that the ^{26}Mg anomaly arises from the decay of the unstable aluminum isotope ^{26}Al early in the history of the solar system.

The half-life of ^{26}Al is about 700,000 years and its decay has long been postulated as the heat source that caused the parent bodies of the achondrites to melt and give rise to the characteristic features of these objects. The melting process is believed, on the basis of radiochemical dates, to have been completed within the first few million years after the solar system formed, 4.6 billion years ago. Other candidates for the heat source, such as bursts of radiation emitted by the sun, suffer the difficulty that the chondritic meteorites, formed at the same time, did not melt. Thus, the Allende minerals provide the first evidence that ^{26}Al may in fact have been present during the early years of the solar system.

What is still controversial is whether the ^{26}Al, with its geologically short half-life, was produced by a burst of high-energy protons after the solar system was formed, or was an extrasolar ingredient like Clayton's ^{16}O dust grains. An extrasolar source might be a supernova, since ^{26}Al is known to be produced in one shell of exploding stars. For extrasolar ^{26}Al to be incorporated in planetesimals, however, would require that the formation of the solar system take only about a million years, rather than the previously accepted figure of 100 million years. Revising the time scale would also require revision of some radiochemical chronologies, such as those based on iodine and plutonium, and would raise questions about the rubidium-strontium and lead radiochemical dating methods. An extrasolar origin for ^{26}Al is thus disputed by Lee and other investigators, although the proton-burst origin he postulates is an admittedly imperfect model.

Irradiation processes within the solar system have also been proposed to explain high levels of ^{22}Ne and other anomalous patterns of neon isotopes in meteorites. The anomalies, discovered earlier by David Black of the Ames Research Center in Mountain View, California, are complicated because there are many plausible sources of neon, but there is now general agreement that as much as 10 percent of the ^{22}Ne cannot be explained and might be extrasolar. Robert Walker of Washington University, St. Louis, believes that production of the anomalous neon by a burst of protons is possible, but would require radiation of very special characteristics. In one model, for example, the protons would have had to be more energetic than 6 million electron volts to cause the observed effect and no others. He points out that there is no independent evidence of such an irradiative process, and that such explanations do not seem "overwhelmingly convincing." The alternative, again, seems to be an extrasolar source, such as a nova or a supernova close enough in time and space to the formation of the solar system that the anomalous neon was not thoroughly mixed throughout the nebular cloud.

A Supernova Trigger?

That a supernova may in fact have been the source of all of the anomalies so far observed has been proposed by A. G. W. Cameron of Harvard University. His preliminary model—described as "very bold" by many of those at the AGU session—suggests that a supernova explosion triggered the collapse of a dense interstellar cloud to form the solar system. Isotopic anomalies are thus the consequences of nucleosynthesis in this one supernova, which may have contributed as much as 2 percent of the mass of heavy elements in the solar system. The triggering mechanism, as Cameron sees it, was the increase of heat and pressure that caused the interstellar cloud to compress and collapse; because the heating was uneven, density variations led to fragmentation of the cloud. Material ejected from the supernova mixed unevenly with the collapsing cloud, giving rise to the inhomogeneities observed by Clayton and others.

The nucleosynthetic processes within a supernova are not entirely understood, and some details are model-dependent, but the major nuclear reactions and their products within each of several different shells or regions of the expanding stellar envelope are known. What is called a type-II supernova, for example, makes nearly pure ^{16}O in two shells, and much smaller quantities of ^{17}O and ^{18}O in another shell. Neon is also manufactured in two different shells, according to Cameron, one producing mostly ^{22}Ne and the other ^{20}Ne. The radioactive ^{26}Al originates, as far as is known, only in a supernova, and in quantities that appear to correspond with what the isotopic evidence suggests. Isotopes of both krypton and xenon, for which anomalies have been observed, are also manufactured in supernovae—in fact, Cameron speculates, the xenon anomaly data may ultimately provide a basis for estimating the mass of the supernova. Although many of the details of his model remain to be worked out, Cameron believes that it can account for the observed phenomena and will, moreover, be easy to test as more isotopic anomalies are discovered and compared to supernova models.

The supernova model, and even the concept of presolar dust grains, have not yet eliminated other possible explanations for the isotopic anomalies. Other contenders include the proposal of now-extinct superheavy elements that underwent fission, which was advanced to explain part of the xenon anomaly. And there is some negative evidence—isotopes that do not show anomalies—that puts constraints on the theoretical flights of imagination. Lawrence Grossman of the University of Chicago, for example, looked for differences in the pattern of osmium isotopes in the Allende meteorite and terrestrial rocks, and found no large effect. Osmium is a very refractory element, evaporating at 1950°C, and its isotopes have different nucleosynthetic origins. If anomalies are due to presolar grains of dust that failed to evaporate in the solar nebula, Grossman argues, then osmium should be a good element to see them in. Thus, his result can be interpreted as placing a constraint on models of heavy element nucleosynthesis.

Only a few elements have been carefully examined for anomalous isotope patterns so far, so more definite clues to the origin of the solar system can be expected. One of the most obvious abundant elements to examine is silicon; like oxygen, it has three stable isotopes, the lightest of which is made by a different nucleosynthetic pathway than the others. As it happens, Clayton's technique for extracting oxygen from meteoritic rocks extracts silicon too. So he is in the process of reanalyzing hundreds of bottles of previously collected material, in the expectation of finding anomalously high or low amounts of ^{28}Si. Other investigators are also busy, because there now seems to be a consensus that the isotope data are no longer an awkward curiosity. Rather, now that the different pieces of evidence seem increasingly to point in a common direction, this area of research appears to be one of the most promising means of clarifying the prehistory of the solar system.—ALLEN L. HAMMOND