METEORITICS

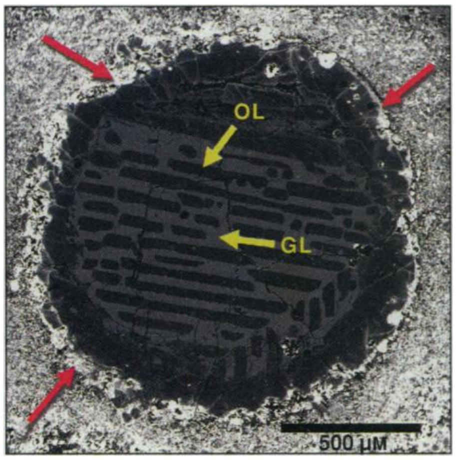
Chondrites and the Solar Nebula

Adrian Brearley

For the inquisitive human mind, among the most tantalizing and intriguing questions is that of how our solar system formed. The answer lies, at least in part, within the asteroid belt, a zone 2 to 4 astronomical units from the sun, between the orbits of Mars and Jupiter, which contains hundred of thousands of small, rocky planetesimals. The asteroid belt is the source of an important group of meteorites, known as chondrites because they contain abundant millimeter-sized silicate spherules called chondrules (from the Greek word "khondros" meaning granule) (see figure). The chondrites formed 4.56 billion years ago within the solar nebula, a disk of collapsed dust and gas that was the birthplace of our sun and the planets (*1*). The chondrites have remained relatively unchanged since they formed and hence provide a record, albeit imperfect, of early solar nebular processes. One of the major challenges of meteoriticists is to unravel this record to provide constraints on the type and duration of processes that occurred within the solar nebula. Such information is critical as input data for large-scale models of the solar nebula (*2*).

Although it is tempting to view chondrites as the pristine, unaltered products of solar nebular processes, in fact there is considerable evidence that many chondrites have been affected by later, secondary alteration (*3*). These processes have overprinted some of the primary characteristics of chondrites to varying degrees, thus creating considerable complexities in their interpretation. To address some fundamental questions about the nature, timing, and location of these alteration processes, a group of some 100 scientists met recently at a workshop in Hawaii (*4*). The meeting highlighted the fact that there are two highly divergent views of secondary alteration processes in chondritic meteorites that have, in fact, existed for many years but are currently the subject of renewed vigorous and stimulating debate in the light of recent studies. Basically, two extreme models have been proposed: one in which the alteration occurred dominantly within the solar nebula, before coalescence or accretion of all the different meteoritic components into a parent body (asteroid), and the other holding that alteration occurred after accretion within the interior of an asteroid. The differences between these two scenarios are by no means trivial because they have far reaching implications for astronomical models of the solar nebula.

A widely recognized type of secondary alteration in chondrites is termed aqueous alteration (*5*), which has resulted in the formation of water-bearing minerals such as clays. It is often observed in a subgroup of the chondrites, the carbonaceous chondrites. For almost 20 years, it has been generally accepted that hydrous alteration in chondrites occurred within a parent body or asteroid and not within the solar nebula. However, in 1993, Metzler, Bischoff, and Stöffler (University of Münster) presented evidence (*6*) from a study of the CM group of carbonaceous chondrites that alteration of some components occurred before their final incorporation into the meteorite parent body (termed preaccretionary alteration) and did not suffer significant alteration after accretion. Much of the discussion at the workshop centered around evidence for and against this model. One of the main arguments for nebular alteration is that unaltered and highly altered materials coexist in the same meteorite. Proponents of parent-body alteration pointed out that CM chondrites sometimes contain veins, presumably pathways for fluid movement, that crosscut the meteorite, providing strong evidence that alteration occurred after accretion. From the workshop, it was apparent that many of the arguments for and against the two models are based on complex textural relations between different minerals. Unfortunately, in many cases the interpretations of these textures are open to ambiguity. At present, the resolution of these questions requires a detailed understanding of the alteration behavior of different minerals under the physical and chemical conditions appropriate to meteorites, clearly an area for fundamental research in the future.



Chondrule from the Allende meteorite as seen through a scanning electron microscope. The characteristic secondary alteration is evident in the form of a thin rim, enriched in iron (brighter, arrowed), around its periphery. The interior of the chondrule consists of bars of olivine $(Mg,Fe)_2SiO_4$ (OL) in a matrix of glass (GL).

The second major topic of discussion at the workshop focused on the evidence for both oxidation and metasomatism in a group of chondrites called the CV carbonaceous chondrites. These two processes may be linked and involve the oxidation of iron metal to iron oxide and the introduction of the volatile elements sodium, potassium, and chlorine, in addition to iron, into different components in the meteorite.

These phenomena are widely observed in the famous Allende meteorite, which produced a spectacular fireball as it fell to Earth on 8 February 1969 at Pueblito de Allende in northern Mexico. Until quite recently, the general consensus has been that the secondary oxidation and metasomatic processes that affected the Allende meteorite and similar carbonaceous chondrites occurred by interaction with gases within the solar nebula and that almost no alteration occurred after these components accreted together into their parent asteroid. This view has recently been challenged by several workers, including Tomeoka and Kojima of the University of Tokyo (*7*) and Krot and coworkers of the University of Hawaii (*8*). These researchers have presented evidence that Allende experienced an episode of aqueous alteration that produced clay minerals, followed by a period of heating (or metamorphism) at temperatures estimated to have been between 300° and 400°C, during which complete dehydration of the hydrous clay minerals occurred. This model is highly controversial because it interprets many of the features previously attributed to gas-solid interactions in the solar nebula to reactions within a parent body. It also requires a parent-body history much more complex than has previously been thought. Thus, the essence of the debate is whether Allende has almost never seen a molecule of water in its history or whether it has, in fact, evolved in an environment something akin to the Florida Everglades, saturated with water.

These remarkably diverse views of the same meteorite emphasize the incredible

The author is at the Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131, USA. E-mail: brearley@unm.edu

challenge of trying to understand the complex record produced 4.56 billion years ago by processes many of which may have no terrestrial analog. At the workshop, these different models were vigorously debated, and several lines of evidence to support both models were presented. It would be inaccurate to say that the differences between the different protagonists were completely resolved and everyone went home happy. However, the workshop was highly successful in highlighting future areas of research that may help resolve some of these key issues, perhaps involving collaborations between scientists with highly divergent views. The challenge now is to try to reconcile many apparently contradictory observations into some sort of coherent model. Whatever the outcome, this process will undoubtedly lead to revelations about a meteorite that has already stimulated and intrigued many planetary scientists for the last 25 years.

References

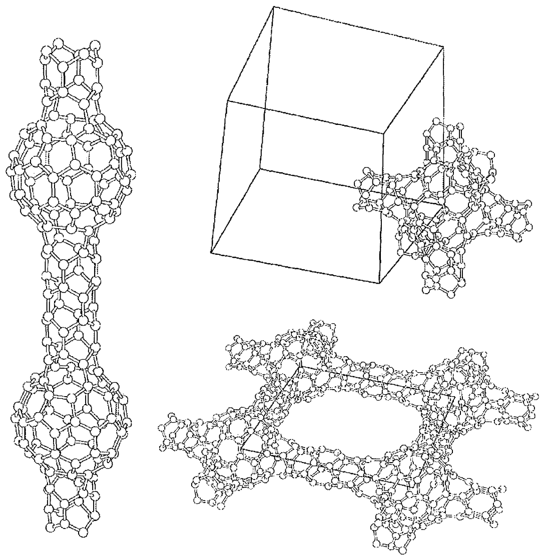
1. S. R. Taylor, *Solar System Evolution: A New Perspective* (Cambridge Univ. Press, Cambridge, 1992).
2. P. Cassen, in *Chondrules and the Protoplanetary Disk*, R. H. Hewins, R. H. Jones, E. R. D. Scott, Eds. (Cambridge Univ. Press, Cambridge, 1996), pp. 21–28; A. P. Boss, *ibid.*, pp. 29–34.
3. G. J. MacPherson, D. A. Wark, J. T. Armstrong, in *Meteorites and the Early Solar System*, J. F. Kerridge and M. S. Matthews, Eds. (University of Arizona Press, Tucson, 1988), pp. 746–807; X. Hua, J. Adam, H. Palme, A. El Goresy, *Geochim. Cosmochim. Acta* **52**, 1389 (1988).
4. M. Zolensky, H. Y. McSween Jr., in *Meteorites and the Early Solar System*, J. F. Kerridge and M. S. Matthews, Ed. (University of Arizona, Tucson, 1988), pp. 114–143.
5. Workshop on the Nebular and Parent Body Alteration of Chondritic Materials, Maui, HI, 17–19 July 1997.
6. K. Metzler, A. Bischoff, D. Stoffler, *Geochim. Cosmochim. Acta* **56**, 2873 (1992).
7. T. Kojima and K. Tomeoka, *ibid.* **60**, 2651 (1996).
8. A. N. Krot, E. R. D. Scott, M. E. Zolensky, *Meteoritics* **30**, 748 (1995).

APPLIED PHYSICS

Carbon Nanotubes for Next-Generation Electronics Devices

Susumu Saito

The age of semiconductor technology started in 1947, just a half century ago, when the first semiconductor device, a germanium-based transistor, was invented at Bell Telephone Laboratories. Since then, the miniaturization of devices has been continuous, and computers have become faster and smaller. Meanwhile, silicon has become the most popular device material, owing to its geological abundance and suitable physical properties. Nowadays, the size of the typical device is halved every 3 years. But how far can we go along this road? Although the present devices consist of tiny material domains and junctions between them, each domain is designed to behave in the same way as its macroscopic counterpart. Hence, the present path should end when we go from the present micrometer (~10 μm) world to the nanometer (~10 nm) world where materials are known to behave quite differently because of quantum effects.



Nanotubes and fullerenes may be useful as constituent units of carbon nanoelectronics device. [Adapted from Hamada (*5*)]

At the present pace of miniaturization, we will reach this end within a decade. In order to overcome this technological limit, several types of devices are being investigated that make use of quantum effects rather than trying to overcome them. For this reason, the nanometer-scale carbon materials, namely the fullerenes and nanotubes (see figure), have attracted great interest not only in the scientific fields but also in the field of semiconductor technology. Solid C_{60} is semiconducting (*1*), whereas nanotubes are predicted to be semiconducting or metallic, depending on their network topology (*2*), and several device structures have been theoretically proposed (*3*). On page 100 of this issue, Collins *et al.* report an experimentally functioning carbon nanodevice based on nanotubes (*4*).

In general, there are two kinds of elemental device structures: two-terminal and three-terminal devices. The transistor is a three-terminal device with a variety of structures, materials, and basic functional mechanisms. A typical two-terminal device is the diode, having also a variety of structures and applications, such as switching, rectification, and solar cells. The "nanotube nanodevice" reported by Collins *et al.* is a kind of nanodiode.

Collins *et al.* took a novel approach in using a scanning tunneling microscope (STM) as nanotube manipulator. The tip is first used to pick up and retract the nanotube rope, and then it is used as a sliding local probe to measure the electrical conductivity between the tip and substrate, connected by means of retracted tubes. They found an abrupt change in the current flow from that in a graphite wire to that in a device upon sliding the tip in one direction. Beyond certain well-localized positions, the current can flow only in one direction, which is called rectification, the fundamental function of the two-terminal diode device.

In semiconducting materials, a small amount of impurity added as a dopant can make electron-excess *n*-type or electron-deficient *p*-type semiconductors. A junction between *p*- and *n*-type semiconductors works as a diode. A rectifying junction can also be formed between a semiconductor and a metal. In the case of carbon nanotubes, they can be either metallic or semiconducting, depending on the topology. Hence, experimentally observed diode properties can be explained by the presence of the junction between two topologically or electronically different nanotubes.

Such junctions can be designed by introducing pentagon-heptagon pair defects into otherwise hexagonal nanotube networks (*3*). Fullerenes are also known to work as junction units for nanotubes (*5*). Therefore, the next milestone toward fullerene-nanotube electronics would be the construction of topologically designed two- and three-terminal nanostructures.

Carbon is also one of the geologically most abundant elements. Moreover, it can take a variety of forms, as has already been shown in fullerene and nanotube geometries.

The author is in the Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro-ku, Tokyo 152, Japan. E-mail: saito@stat.phys.titech.ac.jp