METEORITES AND THE ORIGINS OF THE SOLAR SYSTEM

D. W. SEARS
Department of Metallurgy, The University, Manchester, England

1. INTRODUCTION

SINCE THE TURN OF the century meteorites have acquired a new place in astronomical thinking and there has been a consequent increase in their study. Since the scientific examination of meteorites began their composition has been thought to give a clue to the composition of the rest of the solar system, and with the advent of the spectroscope a direct comparison with the Sun became possible. Early this century meaningful comparisons could be made and the conclusions drawn are largely still unchanged (Fig. 1). From Fig. 1, in which the solar composition is compared separately with that of meteorites and the Earth's crust, it can be seen that, unlike the Earth's crust, meteorite closely resemble the Sun in their composition. (We here neglect the very light gases like hydrogen and helium which only massive bodies like the Sun and Jupiter can acquire or hold.) The reason is not difficult to see. The Earth is a differentiated system, that is, iron and similar metals (the "siderophiles") have gone down to the core and predominantly rock-forming elements (the "lithophiles") remain on the surface. The Earth being a large body (compared to the meteorites) has gone and still goes through many processes that redistribute elements. It may once have been molten for example, and currently large scale movements of the ocean floor send iron and magnesium-rich silicates plunging great depths into the upper mantle, while aluminium and ium-rich rocks float on this in the form of the continents. Meteorites, by contrast, are comparatively unchanged. They represent "probes" by which we can "see" back to the very origins of the Solar System itself. They carry information not just in their composition, although this is very important, but in other physical properties they acquired during their formation.

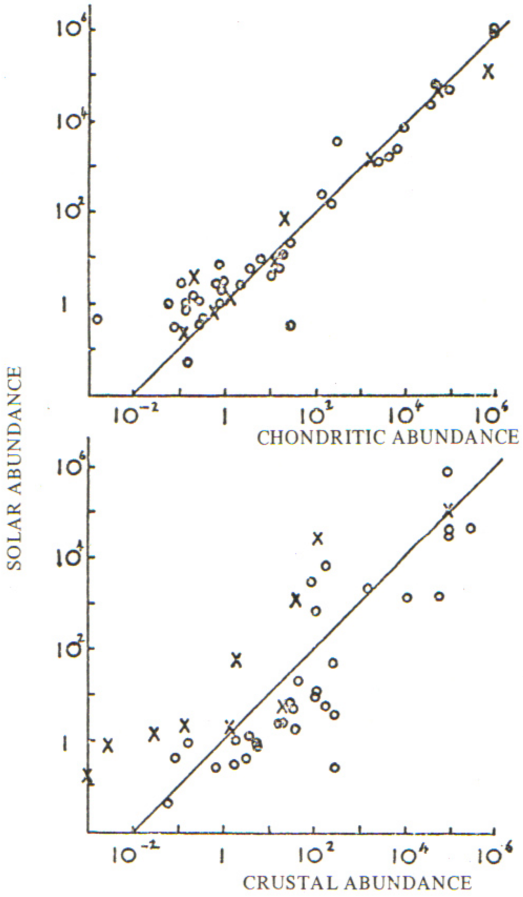

Fig. 1. Comparison of the composition of the Sun (as determined spectroscopically) with that of the chondritic meteorites and the Earth's crust. Each point refers to a different element, the siderophile ("iron loving") elements being plotted as crosses. Meteorites closely resemble the Sun but the Earth's crust is depleted in siderophiles which have gone down to the core. (After Wood, 1968.)

2. ASTRONOMICAL THEORIES FOR THE ORIGIN OF THE SOLAR SYSTEM

Many excellent articles, and indeed books, have been written reviewing the astronomical theories for the origin of the Solar System and we need not dwell long on them here. Broadly speaking they have tended to be of two kinds; those based on an encounter between our Sun and another body, and those based on a primordial interstellar cloud of gas. In the primordial cloud theories the Sun and planets formed by condensation of the gas into the Sun and dust, after which the dust accreted into the planets. The former mechanisms explain the most problematical feature of the Solar System, its angular momentum distribution, while the latter have the overwhelming advantage of indirect observation.

One would reasonably expect that the angular momentum would be distributed in accordance with mass, so that the largest bodies had most angular momentum. But in fact this does not happen. There is an enormous imbalance and the Sun rotates very slowly, its rotational velocity being only one-fiftieth of that expected. Conversely, while the planets have only 0.2% of the mass of the system they have 98% of its angular momentum. However encounter hypotheses have the problem that the event is statistically unlikely; even the proponents of such a theory predict that in 5000 million years the likelihood of an encounter is less than one in 1000. Yet almost every star of solar type has this slow rotation and the process responsible looks very common.

Interstellar nebulae in which stars are condensing are very common, for example the well known Orion nebula (Fig. 2) is such a system. It is true that astronomers cannot see planets in the making but it requires little imagination

Fig. 2. The Great Nebula in Orion in which stars are forming from nebula material. (Photograph from the Hale Observatories.)

to believe the same process occurs on a smaller scale around a star. The problem with this theory is that it does not explain the angular momentum distribution. Hoyle has recently invoked a kind of whiplash action whereby the lanets are speeded up and the Sun slowed down by the magnetic field lines of the Sun. This has run into serious problems since the same action would sweep the dust needed to make the planets out of the system. An alternative by McCrea seems more attractive. He sees the growth of the primordial Sun going by the capture of large minor condensations within the primordial nebula. Eventually instead of the condensation combining with the growing Sun they are captured into orbit about it where they condense and accrete into planets. This process, which is a nebula hypothesis with the angular momentum distribution explained in the same way as in the encounter hypotheses, would take between 6000 and one million years; an astonishingly short time astronomically.

3. THE ORIGIN OF THE METEORITES

It seems now almost universally accepted that many meteorites came in the last instance from the asteroid belt. The only direct evidence for this is that the two meteorites whose orbits are accurately known have aphelia in the asteroid belt (Fig. 3). It seems remarkable that with over 500 meteorites falling a year that we should know reliable orbits for only two of them. However, it is necessary for the meteorite's fireball to be photographed by many cameras so that a trajectory can be calculated accurately by triangulation and it is only recently that camera networks have been set up for this purpose.

However besides this direct evidence there is a considerable quantity of circumstantial evidence pointing to an teroidal origin. For example, the iron meteorites have stalline textures the fineness of which indicates the rate of cooling, coarser textures cooling slowest. These indicate between 1 and 10 K per million years which in turn point to parent bodies of less than 1000 km since larger bodies would cool much slower. This is precisely the size of the larger asteroids. Recent developments may modify these values downwards into the size regions of most asteroids. Another example of evidence which points to an asteroidal origin is the inert gas content. Many meteorites have textures similar to lunar rocks indicating that they were once surface debris caused by multiple meteorite impact. While in the form of a surface debris the solar wind implanted numerous inert gas isotopes which can now be measured. Such a history places considerable restrictions on the location for these events since it requires a specific cratering rate and solar wind flux. Both seem appropriate to the asteroid belt. Finally the recent reflectivity spectra results of McCord and Adams constitute circumstantial evidence for a link between the asteroids and certain classes of meteorite. The reflectivity spectrum of a substance provides a "finger-print" which is governed by composition and texture and many asteroids resemble meteorites in these respects, especially a class known as the carbonaceous chondrites.

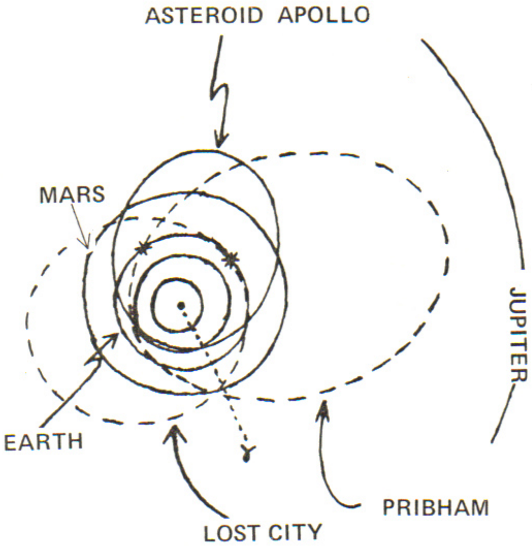

Fig. 3. The two known meteorite orbits. The meteorites fell near Lost City, Oklahoma, and Pribram, Czechoslovakia. Also marked are the orbits of an Earth-crossing asteroid Apollo, and the Earth. The remaining orbits from the Sun outwards are Mercury, Venus, Mars and Jupiter. The asteroid belt lies between the orbits of Mars and Jupiter. (After Fireman and Spannagel, *Chemie der Erde,* **30**, pp. 83-101, 1971.)

The asteroids have always been much the same as they appear now and it is almost certain that they were never a single large planet. Most types of meteorite contain numerous signs of wear and tear due to multiple collisions in space. This may be indicative of the process during which the dust accreted into planets, the only difference being that in the meteorite's case some factor, probably the disruptive influence of Jupiter's gravity, stopped the process before the planet formed. During collisions in space a carbon-rich class of meteorites had its carbon shock-converted into diamonds. For a short while these were thought to indicate very large meteorite parent bodies, Moon or perhaps even Earth-sized. But this is now known not to be the case because, besides the chemical evidence mentioned earlier, there are several minerals found in meteorites that could not have survived

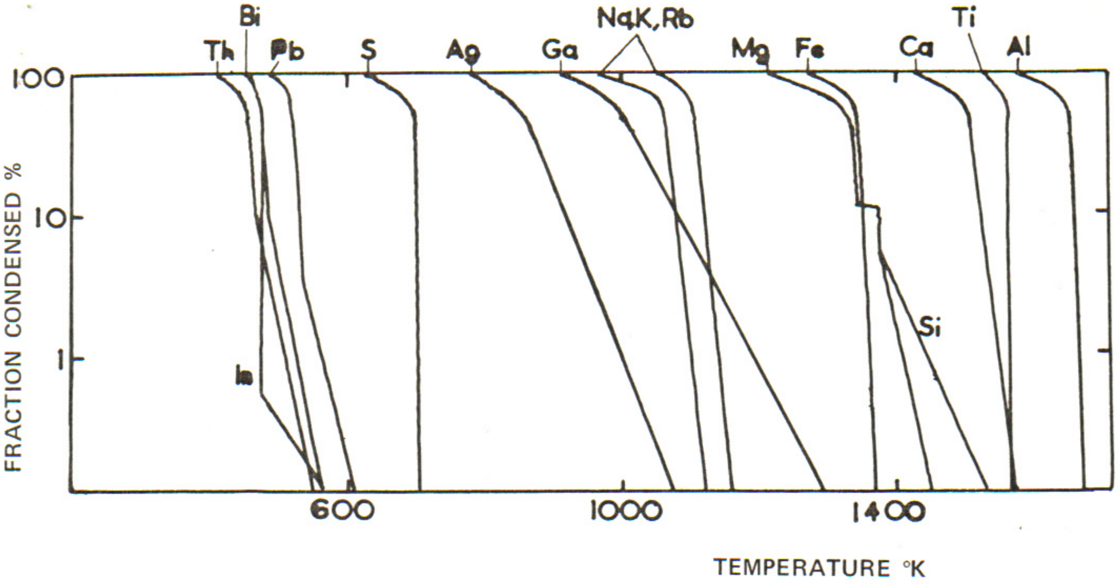

Fig. 4. The condensation paths for some elements in the primordial nebula. It can be read from the diagram, for example, the iron (Fe) begins to condense just below 1400K and is fully condensed by 1300K. (After Grossman, 1975).

high pressures.

Meteorites have the same solidification ages as the Earth, about 4,600 million years. This has been known for well over a decade and recently it has been found that the Moon also solidified at about this time. It seems probable that most of the Solar System has this age. We may assume therefore that meteorites were formed in the asteroid belt at the same time as the rest of the Solar System formed. Furthermore they have largely remained chemically unaltered and were made from the same starting material as the Sun. Starting from these premises we may look now at the meteorites and see what they can tell us about the origin of the Solar System.

In the early nineteen-sixties, while examining the inert gas content of the Richardton meteorite, Reynolds found a remarkable enrichment in a particular isotope of xenon, xenon-129. The nuclear systematics are such that this could only have been produced by iodine-129. But this isotope has a very short half-life (17 million years) so that when the meteorite was put together and could trap xenon in its fabric only a few tens of millions of years could have elapsed since the elements making up the meteorite were last in an element forming environment, that is a star. Recent advances in mass spectroscopic techniques have enabled this conclusion to be confirmed using other isotopes (rubidium-87 and strontium-87) and other meteorites. It now seems well established that the time the meteorites, and therefore probably the Solar System, took to form was very brief, say less than 50 million years.

The meteorites which most closely resemble the Sun in composition and which probably most closely resemble their original forms are the carbonaceous and ordinary chondrites (so-called because they contain silicate spherules or "chondrules"). Many of the properties of meteorites can be explained by imagining their formation from a primordial mass of gas with the cosmic composition. It is possible to follow the processes that occur as this gas cools down using thermodynamic calculations. This line of thinking was initiated by Urey in the 1950s and pursued with much success by several groups in the U.S.A. The first elements to condense somewhere around 1600K were calcium and aluminium because they are least volatile (Fig. 4). The first compounds to be produced were therefore the calcium and aluminium silicates at about 1500K. Remarkably, in some of the carbonaceous chondrites there are large white inclusions visible to the unaided eye consisting of just these minerals (Fig. 5). The next important phase to condense is metallic iron-nickel (at about 1400K) and then other elements condense and react with each other to form a variety of silicates and other minerals. By the time the temperature has reached about 400K water condenses to produce the hydrated silicates observed in some carbonaceous chondrites. Around this temperature also the carbonaceous compounds formed which characterise these chondrites. By mixing the low temperature and high temperature material in various proportions it is possible to produce bodies with the composition and texture of many classes of meteorites. Furthermore the lowest temperature at which accretion occurred can be estimated from the proportions of the most volatile elements present. The condensation temperatures calculated depend of course on the pressure of the nebula, indeed the initial assumption is that condensation occurs when the vapour pressure of an element equals its pressure in the nebula. They suggest something like 10^{-4} to 10^{-6} atmospheres which is very near the value given by the astrophysicists for the pressure of the nebula at the asteroid belt's distance from the Sun (10^{-3}-10^{-4}).

Needless-to-say this simple model has not gone unchallenged. It presupposes equilibrium condensation, for example, whereas some argue that supersaturation would occur due to the lack of nucleation centres in the primordial nebula. Similarly models exist in which ionisation is the driving force for accretion. Nevertheless, the equilibrium condensation models are very popular and so far very successful. Their success in explaining much about the meteorites indicates that the assumed original composition resembles closely the actual original composition. As we saw earlier many elements indicate that the meteorites and the Sun are of similar composition and that the two objects came from the same pool of original material. We have therefore a model which can explain much about the meteorites and the temperatures and pressures it requires could have been found at various times in the asteroid belt.

4. COSMIC DUST

It is almost certain that much dust is reaching the Earth's surface from space, in fact the total weight falling as submicroscopic dust may be a thousand times that falling as meteorites. The recovery of such material might greatly add to the knowledge gained from meteorites since the meteor amera networks have shown that much of the dust is recent ejecta from comets. Comets are important members of the Solar System and they have often been linked in their history with meteorites. Their composition and orbits are the basis of such ideas. Furthermore they may be identified with small residual floccules in the McCrea theory. Comets are bodies for which little direct textural and compositional data exist and consequently much time, effort and money have been spent on collecting cosmic dust. Thousands of tons of polar ice have been melted and the particles filtered out, similarly sedimentary rocks have been dissolved and filtered. The major problem is contamination. Volcanic eruptions of the sort that can fill the upper atmosphere with dust are common. To some extent the problem has been overcome using sounding rockets, satellites and balloons. Sounding rockets and satellites have been reasonably successful at *detecting* dust and so figures for the influx rate are well known. But the major hope for collecting particles rests with the large stratospheric balloons which reach great heights, may stay aloft for many months and whose only source of contamination is the balloon itself.

This important and very difficult area of meteoritic research is in many ways still in its infancy and it may well be that really useful results await permanent manned laboratories in space. For the moment we rely mainly on meteoritic data and the condensation and accretion processes they indicate must be examined in the light of the astronomical theories for the origin of the Solar System.

Fig. 5. A photograph of a slice of the Allende meteorite. The large white irregular inclusions are aluminium-calcium silicates which were among the first elements to condense. They therefore represent the oldest solid material in the Solar System. (Sears and Mills, *Earth and Planetary Science Letters*, **22**, pp. 391-396, 1974.)

5. THE PLANETS

It is an inescapable conclusion that if the process of conensation and accretion was occurring in the asteroid belt it was occurring elsewhere in the system. Similar calculations have therefore been made by Lewis who imagined that the temperature at which equilibration with the nebula ceased varied with distance from the Sun (Fig. 6). Thus Mercury represents the product of condensation at about 1200 K, Venus at about 1000 K and so on out to the asteroids which are analogous to 425 K condensates, assuming they are like the carbonaceous chondrites. Beyond the asteroids the theory has only been used for the satellites of the major planets, not the major planets themselves which are assumed to be miniature Suns. One difficulty of this theory from the meteorite point of view is that it requires that the ordinary chondrites condense within the orbit of Mars, and not in the asteroid belt. It also requires that the Moon condensed at a very high temperature (1600 K) which it could not have experienced in its current position so near the Earth which accreted at a low temperature.

The composition of the planetary atmospheres as determined by spectroscopy and the density of the planets are consistent with the equilibrium condensation model. Inhomogeneous accretion, whereby the core forms first and then the layers of differing composition form one by one,

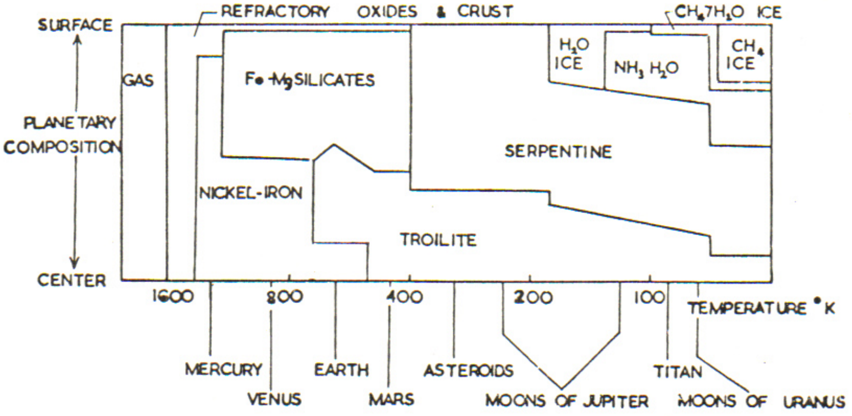

Fig. 6. Lewis' equilibrium condensation model for the composition of the planets. The diagram is read such that the Earth condensed around 600 K and consequently has a small nickel-iron inner core, an outer troilite core, an iron-magnesium silicate mantle and a refractory crust. The major planets are assumed to be miniature Suns and they were not involved in this mechanism. (Lewis, 1975.)

fails on several points. It prohibits the existence of the important mineral troilite (iron sulphide) since iron will be isolated from the nebula when sulphide formed. For similar reasons the iron-magnesium silicates of the ocean floor could not have formed.

The equilibrium condensation model that explains so much about the meteorites seems therefore to also offer possibilities for the planets. It seems very difficult to avoid assuming that all the material of the Solar System condensed from the same original nebula. It also seems certain that it did so very quickly. Encounter theories which produce the planets from a compositionally different body to the Sun and theories which involve a mechanism that would redistribute elements can clearly be discounted. Similarly theories requiring very long periods of time can be disregarded. Unfortunately few authors of theories for the origin of the Solar System consider this important point and they do not calculate how long their mechanism would take to accrete planets. However, in view of both these conclusions McCrea's theory would appear to be very attractive, but whether it will stand the test of time any better than its many predecessors remains to be seen.

BIBLIOGRAPHY

Anders, E., 'Meteorites and the Early Solar System', *An. Rev. Astron. Astrophys.* 9, pp. 1-34, 1971.
Wood, J. A., 'Meteorites and the Origin of the Planets', McGraw-Hill, London, 1968.
Grossman, L., 'The Most Primitive Objects in the Solar System', *Scientific American,* February 1975, pp. 30-38.
Lewis, J. S., 'The Chemistry of the Solar System', *Scientific American,* March 1974, pp. 51-65.
Woolfson, M. M., 'The Evolution of the Solar System', *Rep. Prog. Phys.* 32, pp. 135-185, 1969.

NOTES:

The similarity in meteoritic and solar abundances was first observed quantitatively by H. N. Russell "Composition of the Sun's atmosphere", *Astrophys. J.* 64-67 (1929). Fig. 1 is based on the plots in J. A. Wood, *Meteorites and the Origins of the Planets,* McGraw-Hill, London, 1968. Astronomical theories for the origin of the Solar System have been reviewed by M. M. Woolfson, "The Evolution of the Solar System", *Rep. Prog. Phys.* 32, 135-185 (1969); I. P. Williams and A. W. Cremin, "A survey of theories relating to the origin of the Solar System", *Quart. J. Roy. Astron. Soc.* 9, 40-62 (1968); I. P. Williams, *Origin of the Solar System,* Adam Hilger, London, 1976.

The camera networks for photographing fireballs are described in R. E. McCrosky and Z. Ceplecha, *Photographic Networks for Fireballs,* in P. M. Millman (ed.), *Meteorite Research,* 600-612, D. Reidel Publishing Company, 1968.

The determination of cooling rates from the structure of iron meteorites was described by J. A. Wood, "The Cooling rates and parent planets of several iron meteorites", *Icarus* 3, 429-459 (1964), and J. I. Goldstein and J. M. Short, "Cooling rates of 27 iron and stony-iron meteorites", *Geochim. Cosmochim. Acta* 31, 1001-1023 (1967).

The argument for an asteroidal origin based on gas content was pointed out by E. Anders, "Do stony meteorites come from comets?", *Icarus* 24, 363-371 (1975), and the spectral reflectivity measurements have recently been reviewed by C. R. Chapman, "Asteroids as meteorite parent bodies: the astronomical perspective", *Geochim. Cosmochim. Acta* 40, 701-719 (1976).

Work on the origin of diamond was described by E. Anders, "Diamonds in Meteorites", *Scientific American*, October 1965, 26-36, and M. Lipschultz, "Origin of Diamonds in Urielites", *Science* 143, 1431-1434 (1964).

The early xenon work was reviewed by H. H. Reynolds, "The age of the elements in the Solar System", *Scientific American,* November 1960, 171-182 and recent work by D. Heymann, "The Inert Gases: H^2, Ne^1, Ar^{18}, Kr^{36} and Xe^{54}", in B. Mason (ed.), *Handbook of Elemental Abundances in Meteorites,* 29-66, Gordan and Breach, 1971.

The thermodynamic calculations for a condensing primordial cloud were first described by H. C. Urey, *The Planets: Their Origin and Development,* Yale University Press, 1952 and the recent work reviewed by L. Grossman and J. W. Larimer, "Early Chemical History of the Solar System", *Rev. Geophys. Space Sci.* 12, 71-101 (1974). The alternatives are due to M. Blander and J. L. Katz, "Condensation of Primordial Dust", *Geochim. Cosmochim. Acta* 33 701-716 (1967) and G. Arrhenius and H. Alfvén, "Fractionation and condensation in space", *Earth Planet. Sci. Letters* 10, 253-267 (1972). The application of these techniques to the condensation of the planets has been described by J. S. Lewis, "The Chemistry of the Solar System", *Scientific American,* March 1974, 51-65, and "Metal/Silicate fractionation in the Solar System", *Earth Planet. Sci. Letters* 15, 286-290 (1972).

Sears, D.W. (1977) Meteorites and the origin of the solar system. *J. Brit. Interplan. Soc.*, **30**, 344-348.