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PROBLEMS IN THE STUDY OF METEORITES*†

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Introduction

The fall of meteorites from heaven has been a recognized phenomenon for many centuries. It is stated that the first record is one among the Chinese 6,000 years ago. The Persians, Greeks and Romans considered them as messages from the Gods, built temples over them and revered them. During the Middle Ages they were looked upon as omens of evil, bewitched personages and similar prodigies.

Later, a belief in the possibility of stones fallen from heaven brought forth only ridicule, even from scientific men. Stütz, a famous Austrian mineralogist, remarked, concerning the reported fall of a mass of pure iron at Agram in 1751, that "in our times it would be unpardonable to consider such fairy tales even probable." The German physicist, Chladni, in 1794 first challenged this disbelief and even suggested that meteorites are, in fact, "world fragments." Mineralogists now recognized them for what they are—celestial rocks—rocks with many unusual characters, but amenable to study by the same methods as the better known terrestrial rocks.

The earliest preserved meteorite is one that fell at Ensisheim, Germany, on November 16, 1492. Since then 1,250 distinct meteorites have been recovered, some only as a small individual of but a few grams, others very much larger, even weighing tons. Some reach the earth in thousands of fragments as a shower of stones during a single fall, as those of Pultusk in 1868, when 100,000 fragments are said to have fallen. These 1,250 meteorites can be classified into three rather distinct groups, one made up predominately of stony matter, called aerolites, another almost completely metallic in character, called siderites, and the intermediate forms of about equal proportions of stony and metallic matter, called siderolites. The actual proportion of metallic to stony meteorites must be low,

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for of all the known meteorites actually seen to fall, only 23 are siderites, against several hundred aerolites. The metallic nature of the siderites attracts attention and leads to the more frequent discovery of unwitnessed falls, while the stony meteorites are more easily overlooked.

Minerals of Meteorites

In all, 14 essential minerals have been found in meteorites; the two iron-nickel alloys: kamacite and taenite; the pyroxenes: enstatite, hypersthene, clinoenstatite, clinohypersthene, diopside, augite and pigeonite; the olivines: chrysolite and forsterite; and the feldspars: anorthite, oligoclase and maskelynite.

Characteristic accessory minerals are the two forms of carbon, diamond and graphite; the carbides cohenite and moissanite; the sulfides troilite, daubréelite, oldhamite and osbornite; the phosphide schreibersite and the phosphate merrillite. Quartz and tridymite are exceptionally rare. From the chemical nature of these minerals, one can readily perceive that meteorites have formed in an environment free of water and deficient in oxygen.

Stony Meteorites

Stony meteorites have the mineralogical characters of our terrestrial rocks, and, with the exception of a few accessory minerals, are made up of species not uncommon in our earth. Two types of stony meteorites can readily be distinguished.

The common type of stony meteorites is an aggregate of small shot-like bodies, shaped like öolites. These are called *chondrules* and the rock composed of them *chondrites*. These chondrules are made up either of olivine, enstatite or hypersthene. The important structural and mineralogical types are: (1) barred olivine chondrule with dark glass, (2) porphyritic olivine in a dark glassy base, and (3) radiated enstatite or hypersthene, often with a peripheral or eccentric origin of radiation. Obviously these chondrules have crystallized rapidly from molten droplets of fused silicates. These meteorites may also contain grains of feldspar and dark glass, and they always carry irregular blebs or films of nickel-iron and troilite. The nickel-iron is never found within the chondrules, but occasionally surrounds some. Usually, it is sporadically distributed through the brecciated mass, as if it were a later introduction. Meteorites, like N'gawa and Warrentown, are made up almost entirely of these concretionary bodies. In others the chondrules are largely broken and comminuted.

What is the origin of these strange chondrule bodies? Sorby likened them to a fall of fiery rain and no better explanation has yet been offered. But what were the circumstances of this fiery rain, if such it was? No terrestrial volcanoes yield, or have yielded, such products. Other explanations have been discarded but some promising theories have not been adequately explored. The agglomeratic nature of chondritic meteorites leaves little doubt that they are volcanic tuffs. Many of them show evidences of reheating, in the transition of their minerals, in fused black veins, thermometamorphism and other features.

The universal presence of metallic nickel-iron and of troilite introduces further difficulties of interpretation. There is an apparent relationship between the iron content of the silicates and of the alloys. It must be admitted that, in general, as the iron content of the silicates increases, that of the nickel-iron alloys decreases, as if there was a partition of the iron between the silicate and the metallic portions. Yet there is strong evidence that the nickel-iron is a later introduction, not only later than the crystallization of the chondrules, but after their brecciation. In the unique Cumberland Falls meteorite, obviously made up of fragments of two totally different types of rock, the metallic iron follows the configuration of the fragments as a tenuous film of metal.

A second type of stony meteorite is completely crystalline, like terrestrial rocks, and because they are without chondrules, are called achondrites. Among the achondrites we recognize the types in the table below.

ACHONDRITES AND THEIR TERRESTRIAL EQUIVALENTS

Achondrite	Minerals	Terrestrial Rock
Aubrite	enstatite	enstatolite
Diogenite	hypersthene	hypersthenite
Chassignite	olivine	dunite
Angrite	augite	augitite
Amphoterite	olivine and hypersthene	harzburgite
Nakhlite	olivine and diopside	lherzolite
Eucrite	anorthite and pigeonite	diabase

All of these carry as accessory minerals, nickel-iron alloys in varying amounts.

It is evident that the achondrites correspond to basic terrestrial rocks. Even as the better known earthly basic rocks offer problems of genesis, so their celestial analogues present difficulties to an even greater degree. How can such rocks form from melts, as they apparently appear to have done? In addition, the presence of iron minerals, like the nickel-iron alloys and the iron subsulfide troilite, introduces further problems. For instance, the aubrites consist of pure magnesian enstatite, free from any iron content, as is always found in terrestrial rocks, yet free metallic iron is always present. Have they crystallized with a deficiency of oxygen so that only the magnesium and the silicon have been satisfied, without even a trace in excess to join with the iron? Or have they crystallized from pure magnesium silicate melts, and the iron introduced later?

Some of these achondrites show normal unaltered crystallinity. Many others show varying degrees of fracturing, even to extreme cataclastic granulation.

Iron Meteorites

The second group of meteorites, the siderites, are heavy, compact masses of metal, alloyed iron and nickel, sometimes in huge masses, like Hoba West, weighing sixty tons. In chemical composition they range from 94 per cent iron and 6 per cent nickel, to 70 per cent iron and 30 per cent nickel; in a few doubtful cases they are even more nickel-rich. Accessory constituents are few; troilite, a subsulfide of iron; daubréelite, an iron-chromium sulfide; schreibersite, a nickel-iron phosphide; carbon, diamond and cohenite, the iron carbide, and occasionally magnesium silicates. A small amount of cobalt, usually not exceeding one per cent is always present and there are often traces of platinum and copper. Geophysicists tell us that the core of our earth is probably of a similar nature.

If these iron meteorites are polished and appropriately etched several kinds of internal structures can be developed. The structure can be correlated, in a general way, with the chemical composition of the meteorite.

One class of iron with a nickel content of about 6 per cent is characterized by a well defined cubic cleavage and long, narrow lines, called Neumann lines, that follow the twinning directions of cubic iron. These irons are called hexahedrites.

A second class shows a beautiful basket-weave pattern, resembling the twinning shown by some minerals. The constituent lamellae are arranged parallel to octahedral planes and these meteorites are, therefore, called octahedrites. Close examination reveals two constituents. The coarser lamellae, similar in nature to the iron of hexahedrites, is called kamacite, and a thinner bordering plate of a higher nickel content is called taenite. Often an interstitial eutectic-like mixture of kamacite and taenite is apparent and is called plessite.

The octahedrites range in nickel content from 6–14 per cent, and the meteorites rich in nickel show finer and usually more distinct structures. This is the commonest class of iron meteorite of which characteristic examples are Canyon Diablo, Arizona, and the huge Bacubirito of Mexico,

A third class shows no regular structure of the iron. It may be dense.

felted, flecked, granular or some other irregular fabric. These meteorites are high in nickel, from 15 to 30 per cent. Because of their lack of regular structure they are called ataxites.

The structure of many meteorites may be changed or modified by heating. Hexahedrites become granular, transforming into granular ataxites. Octahedrites lose their regular structure passing into metabolites. Some iron meteorites are found with these secondary structures naturally developed.

The nature of kamacite is now rather well understood. It is α-iron, the body centered form, stable at a low temperature and can carry a maximum of 6 per cent of nickel in solid solution. The kamacite of octahedrites and the iron of hexahedrites are entirely similar. Taenite is much richer in nickel. It is γ-iron, the face centered form, but its exact chemical composition is doubtful. There are some who believe it is an intermetallic compound, Fe_3Ni, but it is generally considered as an alloy of variable composition. The difficulty lies partly in the heterogeneous nature of the samples of taenite analyzed, and probably in the fact that taenite has no fixed composition but can vary within fairly wide limits.

One might expect that a study of the equilibrium relationships of the system iron-nickel, as determined by the physical chemist, would reveal the relationships and origin of these structures without difficulty. But, unfortunately, extraordinary sluggish transitions in significant regions of the diagrams have led to diverse and erratic results. The two forms of iron involved in meteoritic iron structures are α-iron and γ-iron, but intermediate metastable forms may also be involved, if complete equilibrium is not attained. A critical study of meteorite structures may well decide what is the true relationships in the Fe-Ni system and help to define more accurately the composition of the phase fields.

The kamacitic nature of the hexahedrites and their origin through the normal transformations on cooling of nickel-iron of appropriate composition can be accepted as well established. Their only unusual feature is their tremendous grain size. The possible influence of strains or stresses, which have been shown to develop large single crystals from fine grained aggregates, must be considered in this connection. Hexahedral patterns can be induced in artificial iron by violent disruption, as in explosions, and some similar influence may have been active in inducing the characteristic Neumann lines of meteorites. The granulation of hexahedrites by secondary heating accounts for the so-called "low-nickel ataxites."

The structure of the octahedrites, on the other hand, has aroused a great deal of speculation and diverse theories have been offered to explain it. The theory of the origin of Widmanstätten figures is based on the slow cooling of alloys with more than 6 per cent of nickel, with the primary formation of γ-iron. At lower temperatures a γ to α transformation takes place in the solid state, and since the α form (kamacite) has a lower nickel saturation composition than the original alloy, there results a rejection of a high-nickel phase, taenite. When a solid solution, which is stable at high temperatures, precipitates a new phase on cooling, this new phase is deposited in such a way that its lattice bears a definite crystallographic relationship to the lattice of the parent solid solution. This relationship is familiar to the mineralographer in many so-called ex-solution patterns in sulfide minerals. In the case of the Widmanstätten structure in meteorites the dodecahedral plane of kamacite parallels the octahedral plane of taenite. The presence of the eutectic-like plessite has received no adequate explanation.

There is the problem of whether the Widmanstätten structure results from extremely slow cooling within the central core of some body, as our own earth; or by repeated annealings in the passage of the meteorite about the sun; or by some other treatment.

No well established explanation for the various structures of the high-nickel ataxites has been proposed. We are still quite ignorant of the forms of iron that are involved, nor have we determined the role of the frequently occurring phosphides on the structure. Some ataxites may represent pure or nearly pure taenite; others, of lower nickel content, may prove to be metastable forms of iron, or products of incomplete transformation.

Stony-Iron Meteorites

The third class of meteorites is an intermediate type, consisting of both metallic and stony elements in about equal proportions, and are called siderolites or lithosiderites. These fall into two general categories: (1) those carrying olivine, bronzite and sometimes plagioclase in an irregular groundmass of iron, usually of granular texture; and (2) large phenocryst-like olivine crystals in a mesh of octahedral iron. The first group, the mesosiderites, can be considered as stony meteorites with an unusual abundance of iron. The best known meteorite of this type is the Estherville fall. The second class, the pallasites, are a distinct group with unusual structure and relationships.

The olivine of the pallasites may be polyhedral or rounded crystals as in Krasnojarsk, or they may be angular, broken fragments as in Eagle Station, or strongly fractured individuals of a sandy texture as in Imilac. In spite of the intimate association of the olivine with metallic nickel-iron, it is free of nickel and relatively low in ferrous oxide. The problem here is somewhat similar to the apparent anomalous relationship of magnesium silicates and metallic iron in the stony meteorites. The "porphyritic" olivines of the pallasites may be considered as an early crystallization in a matrix of iron. But what about the brecciated olivine like that of Eagle Station? Is the iron a later introduction into a brecciated mass of olivine? Or has the olivine been crushed with a concomitant flowage of the metal?

As in the stony meteorites, a varying degree of oxidation seems apparent. The siderophyr of Steinbach, containing pyroxene and tridymite can be considered as least oxidized. Apparently only enough oxygen was available to combine with magnesium, silicon and a small amount of iron to form the metasilicate pyroxene, leaving, however, an excess of silica unsatisfied. The mesosiderites with both pyroxene and olivine belong to an intermediate step, in which oxidation of the iron did not proceed far enough to convert all the metasilicate into the orthosilicate. In the pallasites sufficient iron is oxidized to induce the formation of the orthosilicate alone. Curiously enough the balance of the elements is inordinately fine, there being no excess of basic elements (other than nickel and iron) or of oxygen, to form more than insignificant quantities of oxides or spinels, a most inexplicable relationship. The rare iron-nickel bearing dunites, and finally the normal dunites, are terrestrial extrapolations of this series.

Age of Meteorites

Some attention has been given to the determination of the ages of meteorites by the helium method, but the results achieved so far are erratic. But no determinations yet made show an age greater than the age determined for our earth. Since meteorites show indubitable evidence of later heat treatment, sometimes of successive heat treatments, it is perhaps more logical to assume that the erratic results obtained are due to the expulsion of the helium. If, because of this removal of helium, these determinations do not give us the ultimate age of the meteorite, they may, under the assumption that all the helium is expelled, give us the time of some important incident in the bodies' history, as, perhaps its last approach near the sun. This assumption is more likely valid for stony meteorites, which lose their helium freely, than for iron meteorites, which hold it more persistently. Reliable data are still very meager, but eventually some interesting correlations may be discovered.

Origin

From whence come these celestial wanderers? And what is their origin? The hypothesis of Chladni, that they are aggregates of matter, the "Urmaterie" from which world bodies might form, still attracts some followers. "The Vermin of the Universe" they have been called. Petrologic evidence, however, points strongly to the fragmentation of a larger astronomical body. One of the difficulties in postulating a common origin for all meteorites is to reconcile the evidence of slow and prolonged heat treatment in the iron meteorites, and the obvious rapid congelation of the stones.

All that we can now say, with reasonable certainty, is that meteorites are basic rocks that have crystallized from molten material in which water was absent and oxygen deficient; that some, the siderolites and siderites, resulted from slow and prolonged cooling, and others, the aerolites, cooled rapidly. There is abundant evidence of tremendous disruption and fragmentation, often followed by later thermometamorphism. It is difficult to avoid the conclusion that they are the debris of some celestial catastrophe.

Whether they were formed at the birth of the moon, the destruction of the missing planet of Olber's, or the dissolution of some other planetary or cosmic mass, I can leave to the decision of the astronomers. It is the mineralogist's province to determine the character of the original body, whatever it may have been, and to follow as far as possible the mutations of its fragments until they come to rest upon our earth. And while the mineralogist may not definitely point to the ultimate origin of these celestial "tramps," he can, at least narrow the field of speculation.