THE COMPOSITION OF METEORITES

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GENERAL DATA

The chemical composition of meteorites gives an indication of their origin. They record cosmic events which have occurred over a long period of time, from the pre-planetary stage, through the thousands of millions of years of their life in space, down to our own time.

Since the end of the last century the composition of stony, iron and mixed meteorites has been directly compared with the rocks of the different shells of this planet. However, the greater the understanding of meteoritic matter, the farther the departure from the familiar ideas of its formation processes

Apart from the astonishing shapes sometimes encountered—ring-shaped meteorites (ataxite Tueson), meteorites with holes, conchoidal surfaces, peculiar crystalline inclusions, *e.g.* the metal plate in the chondrite Timokhina, *etc.*—meteorites are usually large or small angular fragments of a great variety of shapes. During their flight through the atmosphere they become fused and acquire a characteristic surface relief or a fused crust, and are sometimes even tapered to a conical shape. As a rule, the impact of the dense layers of the Earth's atmosphere splits them, especially in the case of stony meteorites. This gives rise to new cracks and shatter zones in their fragments and may even result in polymorphic transformations of meteoritic graphite into minute diamonds[1,2]. On the other hand, the impact pressure developed in meteoritic craters gives rise to more compact modifications of, for example, quartz, which changes into coesite or even stishovite.

The density of stony meteorites is lower than that of the terrestrial rocks with which they are compared, and the porosity of carbonaceous meteorites, for example, may be as high as 20 per cent. This is evidence of their having been formed in the absence of any substantial gravitational field. Stony meteorites (chondrites and achondrites)† are found, which seem to be made up of pieces of light and dark substance. The boundary between them is quite distinct, but uneven. The dark substance is denser and finer-grained, and the light substance contains more chondrules, though they are poorly outlined. About a score of such cases are known, for example in the stony meteorite Cumberland Falls (*Figure 1*) a dark enstatitic chondrite has intruded the light material of an enstatitic achondrite (aubrite)[12]. The light substance scarcely differs from the dark in chemical composition. The dark colour is probably due in this case to the presence of opaque minerals and

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† Besides meteorites, cosmic dust from meteors and comets falls on the Earth. As regards tectites, their origin is still not clear. They have an acid composition (close to rhyolites) with a high potassium content and the usual uranium and thorium content for acid rocks. Spheroids of a metal melt were found in them but ^{26}Al and other cosmic products were not detected. Their origin is therefore limited to the region Earth–Moon[3,4].

carbon[6]. The surprising thing is that the light substance differs sharply from the dark substance of the same meteorite especially in its content of neutral gas isotopes. The light substance contains very little of them, while the dark substance contains thousands of times as many[6].

The brecciated structure of many types of meteorites is very important. This type of stony meteorite consists either of numerous angular fragments of a granular substance or of small sharp mineral fragments (*Figure 2*). These fragments may be either of the same substance as the meteorite as a whole, *e.g.* the so-called monomict breccias, or of fragments from different types of meteorites, *e.g.*, polymict breccias[7]. Among the chondrites, amphoterites and carbonaceous chondrites always have a brecciated structure (*Figure 3* and *4*). which is also encountered in ordinary chondrites. All the so-called basaltic (feldspar-containing) achondrites have a brecciated structure, and some of the feldspar-free achondrites (aubrites, diogenites, *etc.*) also possess it.

With mixed stony-iron meteorites (*Figure 5*), generally classed as breccias, and particularly with mesosiderites, the breccia nature is more pronounced the higher their content of the iron–nickel phase. In turn, their silicate phase is a polymict breccia[7]. This peculiarity of meteorite structure is, on the one hand, an indication of crushing, pulverizing and abrasion processes that have occurred in them during their pre-terrestrial existence, and on the other, as indication that different meteorites are formed by the same agglomerative method from types of matter having different histories. In general, the structure of meteorites depends on the interrelation between the two main immiscible phases of silicate matter and iron–nickel alloy. To the first approximation, stony meteorites fall into the two classes, chondrites and achondrites, according to the finer structure of their silicate matter, chondrites being composed of solidified drops of silicate, called chondrules, ranging from fractions of a millimetre to several millimetres in size, and achondrites being those which do not possess this chondritic structure. Chondrules and chondrite structure are shown in Figures 6, 7 and 8.

COMPOSITION AND CLASSIFICATION OF METEORITES

Schematically speaking, the composition of stony meteorites includes two principal molecules, namely, magnesium orthosilicate, Mg_2SiO_4, olivine with an isomorphic admixture of ferrous orthosilicate, and magnesium metasilicate, $MgSiO_3$, with varying amounts of added ferrous metasilicate (the rhombic pyroxene series—enstatite, bronzite, hypersthene). Other simple silicates encountered are diopside, augite and serpentine, and of the alumino-silicates found in feldspar achondrites, plagiocalses (bytownite, anorthite, *etc.*), maskelynite, silicate glass and others, may be mentioned.

However, all stony meteorites are multi-phase systems which include other oxygen-containing compounds besides silicates, though in smaller quantities. Chromites, and less frequently magnetite, ilmenite, quartz, tridymite are found. Carbonaceous meteorites contain phosphates, chlorides, sulphates, and water†. At the same time meteorites contain a number of compounds of such a nature that they must have originated in an oxygen-free atmosphere under reducing conditions. This is primarily the case with the

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* Some of the minerals are of secondary origin formed, for instance, under the influence of water[8, 9].

iron–nickel alloy phase, which constitutes $\sim$ 12 per cent of chondrites, 20–85 per cent of mixed meteorites and $\sim$ 100 per cent of iron meteorites. All meteorites contain FeS_n—troilite—and to a lesser extent, other sulphides (CaS, MnS, $FeCr_2S_4$) as well as carbon in the form of graphite, organic compounds, diamond, carbides, phosphides, nitrides and other still rarer compounds[10–12].

There is a still more important fact. The meteorite material was initially derived from the plasmic material of the Sun. The existence of all these phases in meteorites is evidence of the simultaneous complex agglomeration of oxides, metal and lower sulphides, carbides and phosphides. In other words, there is no evidence to suggest that the conditions of agglomeration of meteoritic matter were only oxidative or only reductive. Such conditions corresponded to a certain level of cooling solar plasma, possibly an alternative one, which accounts for the variety of compound forms observed and for their ratio in meteoritic matter. On the other hand, not more than 50 minerals have been found in meteorites, while about 3500 have been identified in the Earth's crust, and if mineral varieties are taken into account, this number rises to 5000. This means that the differentiation of matter in meteorites was more primitive than the corresponding terrestrial processes, magmatic or hydrothermal. (This conclusion is of a strictly preliminary nature).

Let us now reconsider the chemical composition of meteorites. Of greatest interest is the fractionation relative to SiO_2/Fe and the distribution of iron in the different phases of stony meteorites, primarily in the metallic phase, as FeO and FeS_n (*Table 1*). The sum of all the forms of iron is constant in all types of chondrites, being close to 25 per cent. Urey distinguishes chondrites rich in iron (28 per cent) and poor in iron (22 per cent)[21]. At the same time as the table shows, carbonaceous chondrites contain mainly ferrous oxide and very little iron, while enstatitic chondrites contain iron mainly in the metallic phase and have very little as ferrous oxide, *etc*. Ordinary chondrites average about 12 per cent of metallic iron. In the Fe/FeO diagram all chondrites fit on the same line (*Figure 9*). The amount of nickel in the metallic phase (usually 6–8 per cent in the iron-phase) rises inversely with this phase content in chondrites. The less there is of the iron phase (and, therefore, the more ferrous oxide), the more nickel there is in it. This is known as the Prior rule[†], which is significant only for chondrites.

All chondrites contain an average of about 6 per cent FeS_n. The principal bases of the silicates are magnesium oxide and ferrous oxide. The alumina and calcium oxide content is insignificant. The time and order of formation of ferrous sulphide is not clear. Probably there are several ferrous sulphide generations, but the nickel content in troilite is considerably lower than in the iron–nickel metallic phase, and as a rule lower than 1 per cent[22]. Enstatitic chondrites[‡] contain much greater quantities of a number of rare chalcophilic and other dispersed elements and primary neutral gases. Thus, three groups or types of chondrites can be distinguished—ordinary (containing olivine, bronzite and hypersthene), enstatitic and carbonaceous. If

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[†] This rule is not applicable to achondrites; see the nickel content in the metallic phase or ureilites, diogenites and other achondrites.

[‡] In the metallic phase of enstatitic chondrites 2–18 atomic per cent of silicon has been found[23].

Table 1. Chemical composition of chondrites (in %)

Chondrites	SiO_2	MgO	FeO	Al_2O_3	CaO	Na_2O	K_2O	Cr_2O_3	MnO	TiO_2	P_2O_5	Fe	Ni	FeS	C	H_2O	*Total iron*	*Reference*
Olivine—bronzite (Nikolskoe)	39.56	24.49	15.03	1.56	1.87	1.20	0.17	0.38	0.24	0.18	0.37	8.0	1.21	6.18	—		24.03	13
Olivine—hypersthene (Saratov)	39.29	25.12	11.72	4.3	2.36	0.91	0.15	0.54	0.31	0.17	0.25	8.56	1.29	4.97	—		21.11	19
Olivine—pigeonite (Felix)	33.95	23.74	22.84	2.91	2.20	0.59	0.05	0.44	0.21	0.10	0.34	4.72	1.36	5.48	—	1.18	26.50	16
Carbonaceous—olivine (Groznaja)	33.78	23.85	28.8	3.44	3.22	0.63	0.20					2	—	5.37	0.68		28.47	17
Carbonaceous—olivine, chlorite (Staroe Boriskino)	26.73	19.35	24.52	3.11	2.22	1.07	0.2	0.3	0.15	0.15		trace	—	2.80	3.75		22.15	18
Amphoterites—hypersthene, breccias (Vavilovka)	39.96	25.32	18.08	1.63	1.80	1.61	0.26	0.15	0.77			1.79	0.93	6.82	—		20.61	19
Enstatite (Indarch,	35.26	17.48	0.00	1.45	0.95	1.01	0.11	0.47	0.25	0.06	0.52	24.13	1.83	14.20	1.17		33.21	20
Pilistvere)	40.66	22.29	0.82	1.38	0.93	0.79	0.16	0.43	0.21	0.12	0.11	21.93	1.75	8.28	—		27.87	20
Average for usual chondrites	38.04	23.84	12.45	2.5	1.95	0.98	0.17	0.36	0.25	0.11	0.21	11.76	1.34	5.73	—	0.25	25.07	21

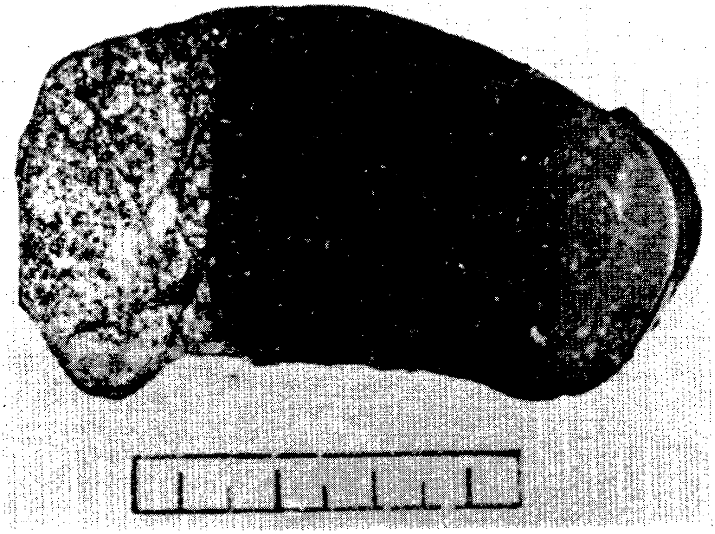

Figure 1. Chondrite—Pervomaisky poselok. Note the light and dark parts of the meteorite

Figure 2. Eucrite—Chervonny Koot. The structure is similar to the structure of the rock diabase. Plates of somewhat dust-covered plagioclase (light) are seen. The spaces are filled with monoclinic pyroxene (grey). The black is a magnetic grain (thin section) ($d = 3{\cdot}5$ mm)

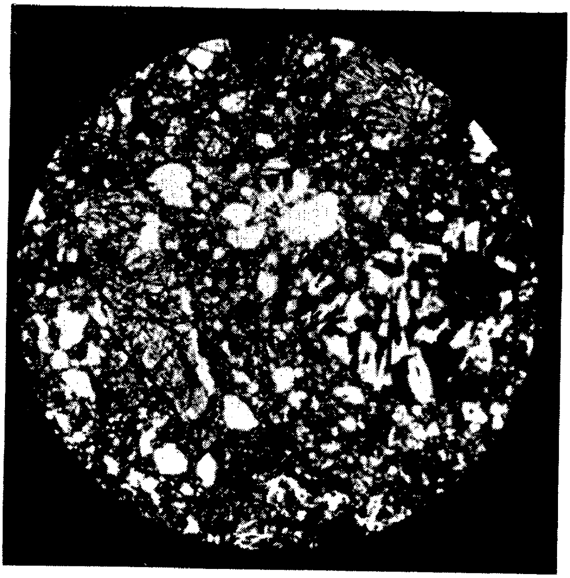

Figure 3. Howardite—Yurtuk. Fragmental structure with fragments of plagioclase and pyroxene grains (eucrite fragments). The largest fragments are of olivine, the smaller of pyroxene, the smallest of plagioclase ($d = 3{\cdot}5$ mm)

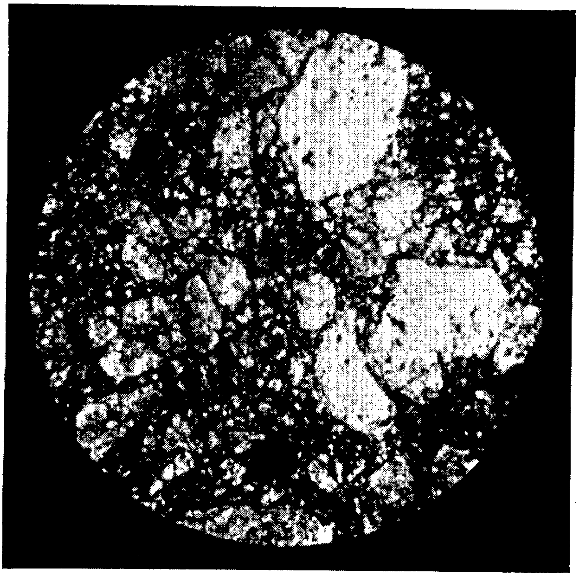

Figure 4. Amphoterite—Vavilovka. It has a brecciated chondrite structure; the chondrite fragments can be seen ($d = 3{\cdot}5$ mm)

Figure 5. Mesosiderite (stony iron)—Nechaevo. In the silicate phase it is a polymict breccia with olivine, pyroxene, iron–nickel alloy and chondrule remains

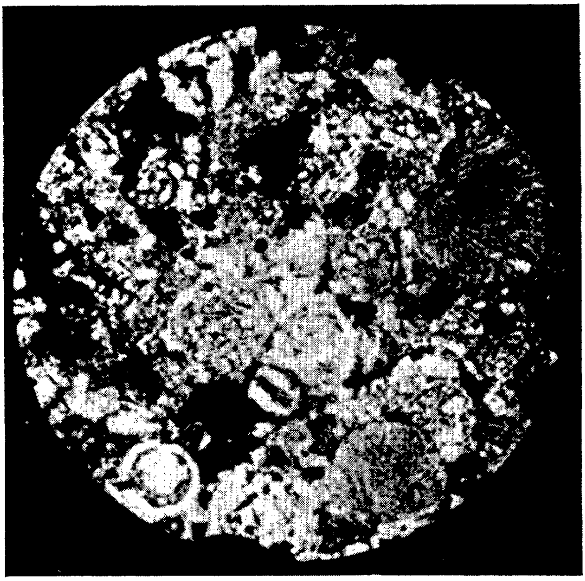

Figure 6. Unaltered chondrite—Alexandrovsky khutor. Chondrules of various sizes are seen ($d = 3{\cdot}5$ mm)

Figure 7. Separate chondrules of the meteorite Saratov

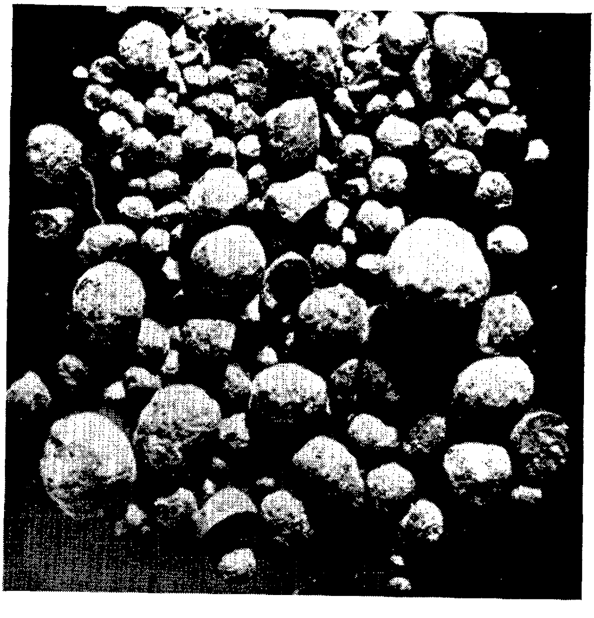

Figure 8. Separate chondrules of the meteorite Nikolskoye

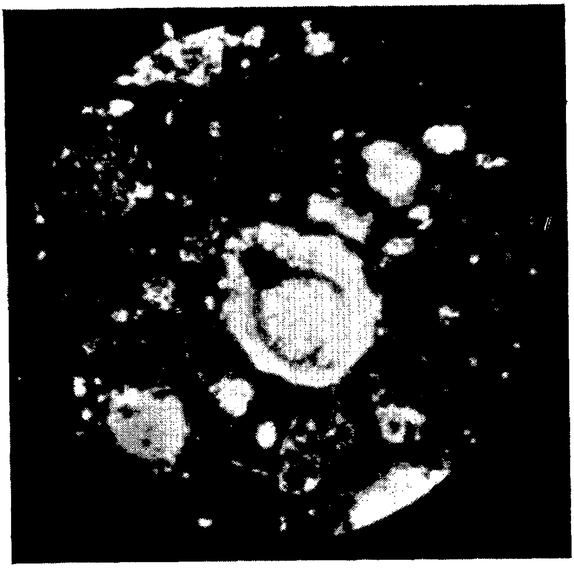

Figure 10. Carbonaceous chondrite—Groznaya. A black opaque mass with separate chondrules and grains of olivine are seen. At the edge of the silicate chondrule is a drop of iron–nickel alloy. The margin, a black ring, is the previous size of the chondrule ($d = 2$ mm)

Figure 11. Feldspar-free achondrite, ureilite—Novy Urei. Note the olivine grains (large, light) with rims of opaque dust. Black carbonaceous matter in the form of spheroidal accummulations ($d = 2$ mm)

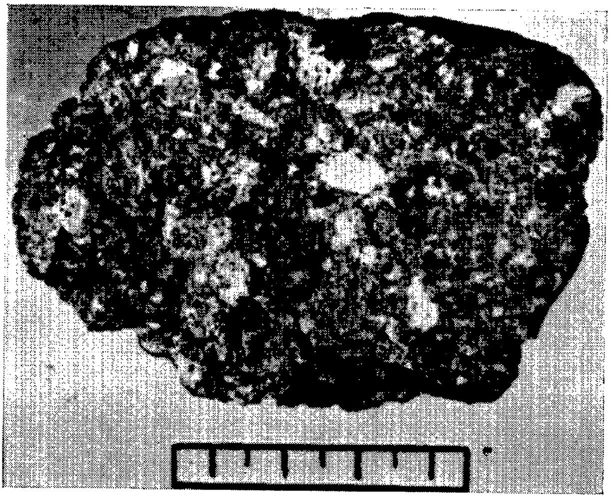

Figure 12. Enstatitic brecciated chondrite—Staroye Pesyanoye. The white and the lighter parts are fragments. Chondrules and large enstatite crystals are seen on the fracture. The black is iron–nickel alloy, oxides and opaque minerals

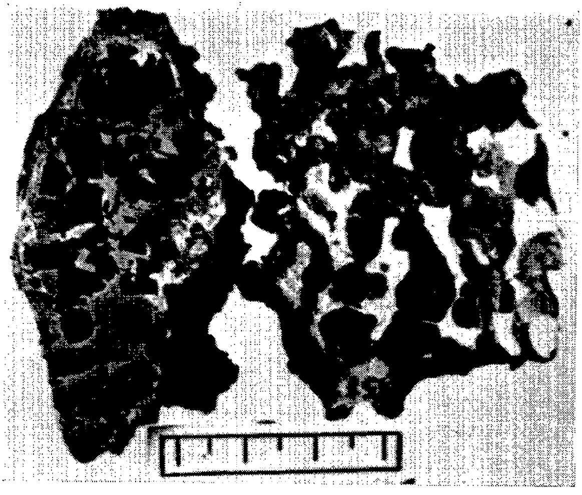

Figure 13. Stony iron meteorites. To the left is Bragin, to the right Pallas iron. On the polished surface the light is the metallic phase, the dark olivine

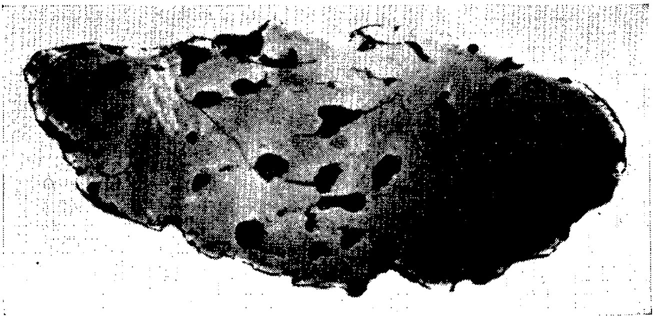

Figure 14. Iron meteorite—Elga. On the polished surface of the iron meteorite are seen impregnations of the silicate phase with a feldspathic composition

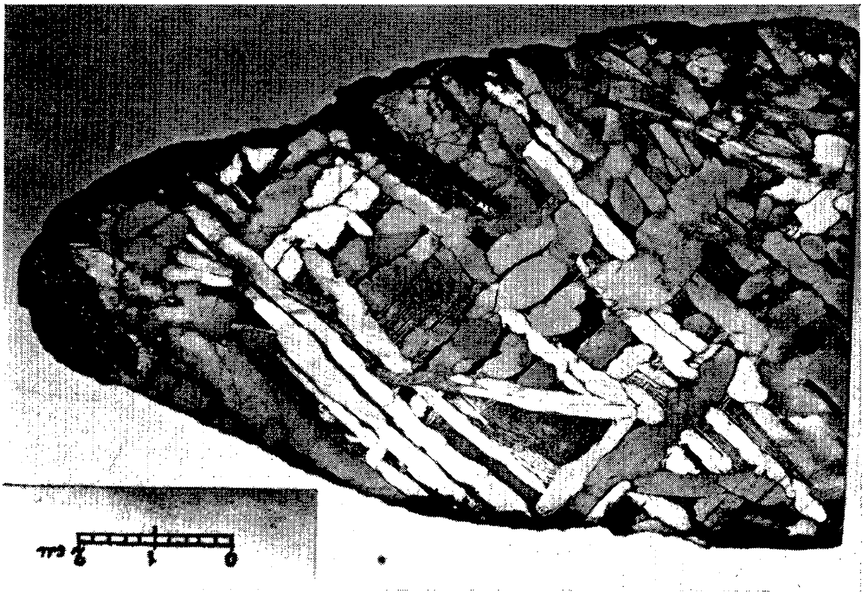

Figure 15. Octahedrite—Chebankol. Note the polished surface and the Widmanstätten structure

Figure 16. Etched surface of the hexahedrite Sikhote-Alin. Note the lumpy structure and the oriented lustre

Figure 18. On the polished surface of the iron meteorite Brenham, sections of Widmanstätten structure and sections of pallasite structure can be seen

their composition is calculated as an atomic percentage not counting water, carbon, sulphur and other volatiles, as was done by Mason, it is found that they all have exactly the same composition. This gives us the right to consider chondrites as a single genetically-related group of meteorites and to speak of their average composition without distorting the true state of affairs.

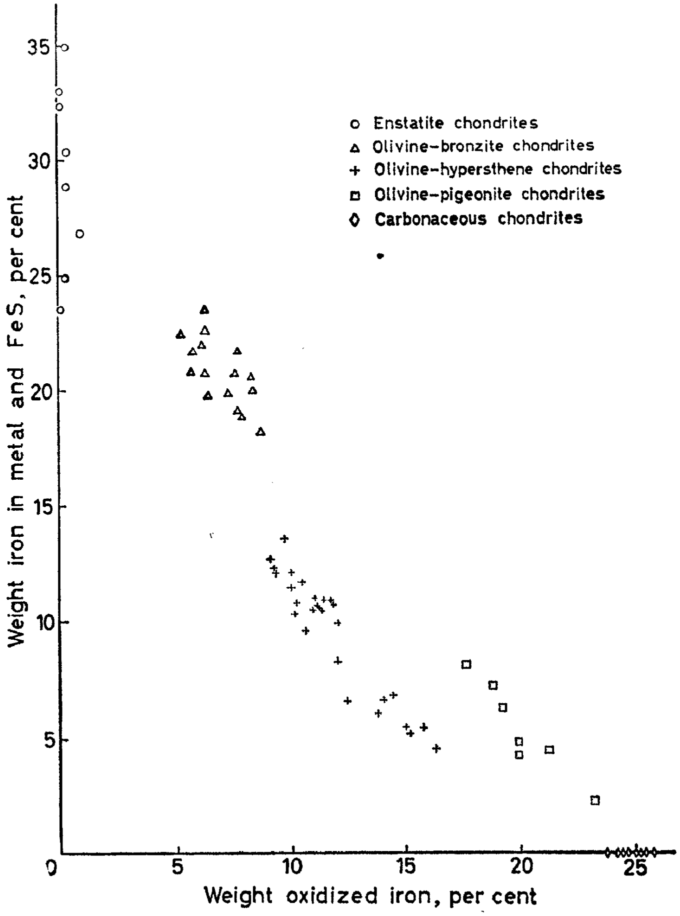

Figure 9. FeO/Fe + Fe(FeS) is shown in the diagram. The disposition of all chondrites along one line is seen (after Mason)

Carbonaceous meteorites, chondrites and achondrites must be mentioned, inasmuch as a great deal of attention has been devoted to them for a number of reasons. Carbonaceous chondrites are not infrequently without chondrules or contain only their shadows (*Figure 10*). All of the 23 carbonaceous chondrites found, *e.g.*, Migei, S. Boriskino, Orgueil Groznaya, Novy Urei (*Figure 11*), are noted for a high carbon content; for instance Orgueil contains 3·5 per cent of carbon, while the usual carbon content of meteorites is 0·1–0·01 per cent. They also contain up to 20 per cent water. Isotopic shifts have been detected in the composition of hydrogen, oxygen and carbon[134, 149].

Owing to the presence of water, carbonaceous meteorites are found to contain serpentine, chlorite, carbonates, sulphates, *etc.* They are higher than other stony meteorites in the dispersed elements bismuth, tellurium, lead, thallium, indium and iodine (and other chalcophilic metals) and contain, as will be seen below, a relatively large amount of primary neutral gases[24, 25].

Carbon is contained in these meteorites in the form of graphite, bituminous organic matter and often as minute diamonds[2, 32, 153]. This is all evidence of the non-equilbrium state of the substance of stony meteorites. The organic matter contains a number of amino acids, purines of complex cyclic hydrocarbons, carbohydrates, *etc.*

The discovery of regular "organized" elements in carbonaceous meteorites resembling spores and microscopic sea-weeds, excited further interest in these meteorites[26–29]. However, it was finally proved that these forms originated on the Earth owing to diffusion of the ferrous chloride (lawrencite), found in meteorites, in traces of water[30]. The presence of high polymeric organic compounds in carbonaceous meteorites gave grounds for the assertion that they are of biogenic origin. However, experiment has shown that these substances (there were no optically active ones among them[31]) are formed from the simple compounds (gases usually ejected by volcanoes on Earth) ammonia, carbon dioxide, sulphur dioxide, water, methane, *etc.*, when mixtures of them are irradiated with protons, neutrons or electrons, or are illuminated with ultraviolet light. It may be conjectured that when the atmosphere on Earth was less dense (and the present-day atmosphere of nitrogen and oxygen of secondary origin was formed biogenically) there was, so to speak, a "window into space" and this radiogenic process could have occurred on the Earth's surface as well.

The minute diamonds in carbonaceous meteorites are formed as a result of the impact pressure. They were first found in this country in Novy Urei, then also in other ureilites, *e.g.*, Goalpara, Dyalpur, as well as in chondrites, *e.g.*, Ghubara, Canyon Diablo[1, 2, 32].

The composition of achondrites is more varied. Besides the $MgSiO_2$ and $MgSiO_4$ molecules, feldspar, diopside and augite are also of importance. This makes it easy to separate two groups of achondrites, *i.e.*, feldspar-free, lacking in calcium oxide and alumina, like chondrites, and feldspar-containing or basaltic achondrites with a high alumina content. These latter resemble in ophitic structure and composition the terrestrial gabbro-diabases which are rich in calcium oxide which partially substitutes the magnesium oxide in them.

Among the feldspar-free achondrites are naclites and angrite having a high calcium content owing to the presence of diopside in the former, and to titanious augite in the latter. Also worthy of mention is chassinyite[†] which consists wholly of olivine with up to 4 per cent chromite and resembles terrestrial peridotites and chromite-containing dunites in composition[33]. As to iron distribution, the total content of all forms of iron in all achondrites is lower than in chondrites, and this value is far from constant. The metallic iron content is below 1 per cent, as a rule (and the content of FeS_n is also low, *i.e.*, about 1 per cent), *i.e.*, the iron is mainly present as ferrous oxide

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[†] The detection of concretion in chassinyite resembling a chondrule, is pointed out[33].

in widely differing amounts. Attention is drawn to the low nickel content ($\sim$ 3 per cent) in the metallic phase of hypersthenic achondrites, diogenites and ureilites. Aubrites (enstatitic achondrites) not only contain no ferrous oxide, but no metallic iron either, while felsdpar-containing achondrites have only traces of metallic iron, though their ferrous oxide content is rather high (higher than in chondrites). This gave support to the idea of loss of iron in achondrites with no exact definition of this term.

Finally, there are meteorites belonging to the class of feldspar-free achondrites, which contain a considerable amount of carbon, *e.g.*, ureilites. The nature of this carbon has already been mentioned. A rise in the content of carbon and neutral gases is not infrequently observed in enstatitic achondrites (aubrites), *e.g.*, in Staroye Pesyanoye (*Figure 12*), which some authors relate to enstatitic chondrites[34, 35]. Feldspathic achondrites *i.e.*, eucrites and howardites, which are mostly breccias containing polymict material as well, therefore have much in common as regards composition: they are equally high in calcium oxide and alumina and contain only traces of iron in the metallic and oxide forms, *i.e.*, still less than feldspar-free achondrites. Hence, feldspathic achondrites have many properties in common, but differ considerably from feldspar-free achondrites, this difference being more pronounced than that between chondrites and feldspar-free achondrites (*Tables 2* and *3*). Achondrites have not been studied very extensively, and new types may be expected to appear. This is all evidence of the considerable variety of processes which led to the formation of these meteorites. There are no grounds for speaking of any average composition covering all achondrites, as these are in relation to chondrites.

Mixed stony iron meteorites, as will be seen below, are regarded as an agglomeration of an iron–nickel alloy with various types of silicate matter from different types of stony meteorites. Indeed iron–nickel alloy is associated with olivine in pallasites, with bronzite in siderophyres, with olivine and bronzite in lodranites and with brecciated achondritic matter in mesosiderites for instance Nechaevo, which has already been mentioned (*Figure 13* and *Table 4*). The only type to which this does not refer is stony iron meteorites with the silicate phase of feldspathic achondrites. In this connection mention should be made of the interesting iron meteorite Elga (*Figure 14*)[51] which contains $\sim$ 85 per cent metallic phase and $\sim$ 15 per cent silicate phase, the latter being mainly potassium–sodium feldspar (anorthoclase ?). Hence, stony iron meteorites differ not only in their iron silicate ratio (their iron–nickel alloy also varies) but also in the nature of their silicate phase as well.

The substance of iron meteorites and of the iron–nickel phase of stony and stony iron meteorites is a solid iron–nickel–cobalt solution containing a number of other elements as well in minor quantities, but in much greater concentrations than in the stony phase. These other elements (platinoids, tin, molybdenum, germanium, *etc.*) form a continuous series of solid solutions with the iron nickel alloy. The solid also contains small amounts of phosphorus, carbon, FeS_n, etc. Thus, this is a complex multicomponent system[53, 54, 123].

Cooling of such alloys involves phase transformations which in the case of iron meteorites result in the various phases and structures found in them. At high temperatures the γ-phase of a solid solution of nickel in iron forms

Table 2. Chemical composition of achondrites (in %)

Achondrites (feldspar-free)	SiO_2	MgO	FeO	Al_2O_3	CaO	Na_2O	K_2O	Cr_2O_3	MnO	TiO_2	P_2O_5	Fe	Ni	FeS	C	H_2O	*Total iron*	*Reference*
Chassiygnites—olivine, chromite 4% (Chassiygny)	37·43	32·16	26·55	1·34	0·52	0·11	0·02	0·98	0·73	0·16	0·07	0·59	0·04	0·88	—		22·39	36
Ureilites—olivine, clinobronzite, carbon (Novy Urei)	39·51	35·80	13·35	0·60	1·40	—	—	0·95	0·43	—	0·05	5·25	0·2	0·36	2·26		16·36	37
Diogenites—hypersthene, dinohypersthene, breccias (Johnstown)	49·83	20·62	13·64	2·33	2·61	0·33	0·10	1·00	0·40	—	0·03	0·84	0·03	1·55	—		12·42	38
Aubrites—Enstatite, breccias (Staroe Pesjanoe)	57·69	37·3	0·04	1·58	0·82	0·16	0·02	0·05	0·16	0·08	—	0·59	0·04	0·88	—		0·60	36
Nakhlites—diopside (Nakhla)	48·96	12·01	20·66	1·74	15·17	0·41	0·14	0·33	0·09	0·38	—	trace	—	0·16	—	0·17	16·75	39
Angrites—titanium augite (Angra)	43·94	10·05	8·56	8·73	24·51	0·26	0·19	—	—	2·39	0·13	—	—	1·26	—	—	7·46	40

Table 3. Chemical composition of achondrites (felds-pathic) (in %)

Achondrites (feldspathic)	SiO_2	MgO	FeO	Al_2O_3	CaO	Na_2O	K_2O	Cr_2O_3	MnO	TiO_2	P_2O_5	Fe	Ni	FeS	H_2O	*Total iron*	*Reference*
Eucrites—pigeonite, feldspar, breccias (Tchervony Koot)	48·80	6·98	18·47	13·44	11·48	0·52	0·12	0·21	0·63	0·71	—	trace	—	0·25	—	14·51	41
Shergottites—augite, maskelynite (Shergotty)	50·21	10·0	21·85	5·90	10·41	1·28	0·57	—	—	—	—	trace	—	—	—	16·98	42
Howardites—hypersthene, plagioclase, breccias (Yurtuk)	49·45	17·40	13·42	9·66	6·39	0·31	—	0·04	0·72	—	0·02	trace	—	0·43	—	11·09	43

Table 4. Chemical composition of stony-iron and iron meteorites (in %)

Meteorite	SiO_2	MgO	FeO	Al_2O_3	CaO	Na_2O	K_2O	Cr_2O_3	MnO	TiO_2	P_2O_2	Fe	Ni	Co	*Reference*
Stony iron meteorites															
Lodranites—olivine, bronzite, iron (Lodran)	28·94	23·33	7·71	0·19	0·18	—	—	—	0·17	—	—	27·77	4·05	7·40	16
Siderophyres—bronzite, tridymite, iron (Steinbach)	34·61	10·08	4·40	—	—	—	—	—	—	—	—	46·02	4·74	—	45
Pallasites—olivine, iron Pallas iron	20·43	23·68	5·86	—	—	—	—	—	0·22	—	0·096	44·02	5·37	0·23	46
Mesosiderites—Hypersthene, anorthites, olivine, iron, breccias (Nechaevo)†	9·50	4·00	8·0	0·2	2·5	0·3	—	—	—	—	—	72·4	2·15	—	9
Iron meteorites															
Hexahedrites (Boguslavka)	—	—	—	—	—	—	—	—	—	—	—	94·05	5·48	—	47
Ataxites (nickel-poor) (Mejillones)	—	—	—	—	—	—	—	—	—	—	—	93·40	5·67	0·66	48
Octahedrites (Ssyromolotovo)	—	—	—	—	—	—	—	—	—	—	—	91·60	7·86	0·44	20
Ataxites (nickel-rich) (Tchinge)	—	—	—	—	—	—	—	—	—	—	—	82·36	16·71	0·40	50

† 25 per cent silica phase

if diffusion takes place on cooling and the γ-phase passes into the α-phase. Therefore phase diagrams of iron–nickel or more complex systems cannot reproduce all the phenomena occurring during the cooling of the iron–nickel alloy, because judging from the absolute age of meteorites, meteoritic matter cools over a period of as much as $4{\cdot}5 \times 10^9$ years. This, in particular, is why there has been little success in reproducing the so-called Widmanstätten figures which form when the surfaces of iron meteorites are etched (*Figure 15*). The transformation of the γ-phase into the α-phase is possible without nickel diffusion (quenching). The phase transformations are probably affected by various admixtures in the iron–nickel alloy the content of which fluctuates. Three phases are known, *i.e.*, kamacite (averaging about 6 per cent nickel), taenite (up to 60 per cent nickel) and plessite (6–34 per cent nickel), the latter being a mixture of kamacite and taenite.

Hexahedrite iron meteorites (*Figure 16*) consist of the α-phase only and contain only kamacite (and consequently little nickel). Iron meteorites containing both phases ($\alpha + \gamma$) are the most common, some of them being of octahedric, others of plessitic (fine-grained) structure. Finally, iron meteorites are known (ataxites) consisting of taenite, which form upon very abrupt cooling of the alloy. The structure of iron meteorites depends on their nickel content. The more fine-structured octahedrites contain more nickel, *etc.* It is not known for certain as yet whether there exists a continuous series of alloys with a range of concentrations of nickel in iron and germanium and gallium in iron, *etc.*, or, as many investigators believe, whether only separate groups of iron meteorites with definite contents of nickel or germanium and gallium, and other elements[69].

It is further observed that in the Sikhote-Alin and other octahedrites, for example, small quantities of taenite (the γ-phase) failed to change into kamacite (the α-phase). On the other hand, a study of the distribution of impurity elements between the iron–nickel alloy and the inclusions which separate out on cooling of the alloy, for instance in FeS_n of schreibersite, rhabdite, *etc.*, shows that this system does not correspond to equilibrium conditions. The FeS_n content in iron meteorites makes up several per cent, but there are iron meteorites containing up to 66 per cent of FeS_n (Soroti iron). It may thus be thought that the variance in composition and structure of the iron–nickel alloy of iron meteorites was caused to some extent by non-constant cooling conditions and the absence of complete equilibrium. There are no grounds at present to assume that the iron alloy cooled at high pressures. The diamonds detected in iron meteorites, in the Canyon Diablo, for instance, can be accounted for quite satisfactorily by the impact pressures developed when they fell on the Earth, which created the conditions for the transition of a part of the graphite into minute diamonds. An influence of high temperatures and pressure over a long period of time is also not necessary for cohenite formation[10].

FRACTIONATION OF THE CHEMICAL COMPOSITION OF METEORITES

From the copious information available on the content of macrocomponents in various meteorites[21, 55–57] one may find and compare the SiO_2/MgO, SiO_2/Fe, FeO/MgO ratios in separate meteorite types. These ratios may also be compared with corresponding ones known for the composition of the Sun *etc.* The differences in the meteorite composition goes much deeper and the microcomponents in their turn show a different content in different meteorites. The distribution of these microcomponents over the meteorite phases depends on their physicochemical properties (lithophylic chalcophylic and siderophylic). As is known, the character of the properties of chemical elements depends primarily on the energy of the bond with oxygen and sulphur. In *Table 5* are listed heats of formation of the sulphides of a number of elements; from this it is easy to predict in which phase a given chemical element will accumulate in chemical processes.

Table 5. Formation heats, ΔH, of sulphides at 18°C (cal/mole)

Sulphides with ΔH lower than FeS	*ΔH*	*Sulphides with ΔH higher than FeS*	*ΔH*
Ag_2S	5·5	PbS	22·3
HgS	11	Bi_2S_3	26·0
Cu_2S	18·97	CdS	34·6
Ga_2S_3	—	In_2S_3	—
GeS	—	Tl_2S	—
As_2S_3	20	Sb_2S_3	35·7
CoS	22·3	ZnS	44
NiS	—	MnS	47
SnS	22·7	WS_2	84
MoS_2	—		

Formation heats of heavy metal sulphides higher than ΔH FeS are of a chalcophile character. Formation heats lower than ΔH FeS are chiefly of a siderophile character.

Considering the silicate phase of meteorites, the amounts of alkali metals and alkaline earths present in this phase in stony meteorites do not vary much nor do they differ greatly from similar amounts in the silicate phase of iron stony meteorites. As a rule the amount of alkali metals, in particular K,Na,Rb,Cs, is somewhat higher in chondrites than in achondrites but unfortunately there have been few analyses of achondrites in this respect. (*Table 6*). Enstatitic and carbonaceous meteorites do not differ in this respect from ordinary chondrites. Alkaline earths strontium and probably barium[5][†] are considerably higher in calcium rich (feldspathic) achondrites, as would be expected. In Stannerne are 60 p.p.m. in Yurtuk 40 p.p.m, in Nakhla 59·6 p.p.m. *etc.* of strontium.

The rare earth content of meteorites differs from that of rocks in having a relatively higher content of the yttric group. The cerium/yttrium ratio for basalts is 2 and for stony meteorites (chondrites) is 1·3. Differences in the rare-earth element composition for various stony meteorites are outlined[59]. Different chondrites (carbonaceous, enstatitic, ordinary) do not differ in their range of transition elements from calcium-poor feldspar-free achondrites. The calcium-rich feldspathic achondrites (Nuevo Laredo, Pasamonte) contain ~ 10 times more rare earths. Olivine from pallasites contains the least amount of other elements.

[†] See difference of the barium content in found (contamination) and in fallen chondrites.[58]

Table 6. The content of alkalis and alkaline-earth elements in various meteorites (parts per 10^6)

Meteorites	Na%	K%	Rb	Cs	Li	Sr	Ba	*Reference*
Chondrites:								
Average	0·7	0·085	5·0	0·12	1·4	11·0	5·0	60, 129, 63–65, 58
Carbonaceous								
Orgueil	0·55	0·045	—	—	1·3	1	1	64, 65
Achondrites (Ca-*poor, feldspar-free*)*:*								
Aubrites								
Norton County	0·07	0·030	4·0	—	0·9	7·5	2·0	60, 129
Staroye Pesyanoye	0·12	0·016	7·0	—	1·5	7·0	—	60, 129
Diogenites								
Johnstown	0·25	0·001	—	—	—	3·0	2·5	60, 129, 65
Achondrites (*feldspathic,* Ca *rich*)*:*								
Eucrites								
Stannerne	0·55	0·055	2·5	—	3·0	6·0		60, 129
Howardites								
Yurtuk	—	0·05	6·0		2·0	40		60, 129
Pasamonte				0·28				
Pallasites:								
(Olivine)	—	0·001	—	—	—	1·0	7·0	

Manganese and titanium do not show any considerable variation, but uranium and thorium are typical lithophils and are concentrated in the silicate phase. Here their content varies noticeably (*Table 7*), but this is possibly connected with the difficulty of their determination. Uranium displays some chalcophilic features, somewhat enriching the sulphide phase (compared with the metal phase) (*Table 7*); Th, As, Sr, (Ba), rare-earths concentrate in Ca–rich achondrites.

The highest halide content is found in carbonaceous chondrites, then in enstatitic chondrites (*Table 8*). However, the fluorine and chlorine contents of the enstatitic chondrites Indarch and Hvittis are markedly different. Achondrites contain the smallest amounts of these elements. It is of interest

Table 7. Uranium and thorium content of various meteorites[61, 66] (parts per 10^6)

Meteorites	U	Th	Th/U
Chondrites:			
Average	0·015	0·040	27
Enstatatitic:			
Indarch	0·009		
Carbonaceous:			
Murray	0·02		
Ordinary Achondrites:			
Aubrites			
Norton county	0·01		
Feldspathic achondrites:			
Eucrites			
Stannerne		0·50	
Nuevo Laredo	0·13	0·54	4
Howardites			
Pasamonte		0·52	
Iron meteorites:			
Toluca (metallic phase)	0·0003	$(\sim 1\cdot 10^{-5})$	(~0.17)
Toluca (troilitic phase)	0·010		
Canyon Diablo (metallic phase)	0·0006	$(\sim 1\cdot 10^{-5})$	(~0·1)
Canyon Diablo (troilitic phase)	0·0035		

Table 8. Halide content in various meteorites (parts per 10^6)

Meteorites	F[67]	Cl[68]	Br[68]	I[24]
Chondrites:				
Hypersthenic				
Mocs	119	173	0·069	0·050
Bruderheim	117	110	0·97	0·016
Bronzite				
Pultusk	133	97	0·17	
Enstatitic				
Indarch	246	900		0·30
Hvittis	122	222	1·04	
Carbonaceous				
Orgueil	206	290		
Achondrites:				
Howardites				
Moore County	60			
Sioux County	64			
Aubrites				
Norton County I	10·7	2·1	0·067	
Iron meteorites:				
Canyon Diablo (Metallic phase)	—	—	—	0·030
Canyon Diablo (troilitic phase)	—	—	—	0·060
Toluca (metallic phase)	—	—	—	0·250
Toluca (troilitic phase)	—	—	—	1·00

that the chlorine/bromine ratio sometimes exceeds 2800 (in Mocs). Iodine is concentrated in iron meteorites mostly in the troilite phase. It is also possible that S, Se, Te may give easily volatile compounds. It is natural that the Se and Te contents in meteorites change in parallel with the change of S content in them. Therefore, meteorites containing much Fe, Sn or S contain more Se and Te. The sulphide phase is enriched in them.

Meteorites	S	Se[96]	Te[24]	Se/Te
Chondrites				
Ordinary				
Beardsley	—	10·8	0·88	12·3
Forest city	2·26	8·6	0·46	18·7
Holbrook	2·75	13·3	0·62	21·4
Modoc	1·38	6.5	0·46	14·1
Carbonaceous				
Murray	2·8	—	1·5	
Achondrites				
Johnstown	—	0·007	0·007	1·0
Nuevo Laredo	—	0·0016	—	—
Iron meteorites				
Toluca (met. phase)	—	—	0·051	—
Canyon Diablo (metall. phase)	—	—	0·054	—
Toluca (troilite phase)	35·4	—	1·7	—
Canyon Diablo (Troilete phase)	35·4	—	5·0	—

Stony meteorites containing relatively more FeS_n or sulphur, as for example carbonaceous and enstatic chondrites, also contain more selenium and tellurium (*Table 9*). At the same time, as we shall see further on, these stony meteorites contain the highest concentrations of iodine and of heavy chalcophilic elements.

As can be seen from *Table 10* and *Table 11* chemical elements which form solid solutions with iron, *i.e.* nickel, cobalt and copper (which to a certain extent is more siderophilic than zinc and cadmium), then germanium, gallium, tin and molybdenum (as we shall see below, all platinoids and gold too) concentrate in the iron phase of stony meteorites. The heavy elements of a distinct chalcophilic character, *i.e.* indium, thallium, bismuth, lead, zinc and cadmium, concentrate in the troilite phase, FeS_n being able to form in different ways, for example in the form of globules during the cooling of Fe–Ni alloys. Thus more in the silicate phase than in other phases, it is found that there is an increase in the content of vanadium and zinc [for instance Zn which is in enstatite chondrites is distributed over the phases as follows (g/t)]:

	Holbrook	*Abee*	*Hvittis*
Silicate phase	50	190	18
Sulphide phase	12	3210	40
Metallic phase	4	280	—

As we already have shown, nickel is actually only present in traces in the silicate phase[61]. Cobalt shows more chalcophilic features than nickel; therefore in troilite nickel/cobalt approaches a value less than ten.

Tin concentrates together with germanium and gallium in the iron phase of iron-stony meteorites[74].

Table 10. Heavy metal content of iron and stony-iron meteorites (parts per 10^6)

Meteorites	V	Cr (%)	Ni (%)	Co (%)	Cu	Zn[70]	Ga	Ge	As	Sn[74]	In	Sb	Tl	Pb	Bi
Iron meteorites:															
Average (88)[69]		0·0037	8·7	0·51	152	22	34	107	8	5	0·0003	0·3		0·2	
Iron phase stony-iron meteorites:															
Average (9)[69]		0·00025	10	0·55	200		18	39		1·0					
Pallasites		0·0008	12·45	0·5	233	1	18	34		1·50					
Brenham		0·0001	10·98	0·6	168		19	63		0·8					
Iron phase of stony meteorites:															
Troilitic phase iron meteorite															
Average (22)[22]	50	0·8	1·3	0·12	50	60	4	8	5	1	0·0021		0·1	12·0	0·1

Table 11. Heavy metal content of stony meteorites (parts per 10^6)

Meteorites	V	Cr(%)	Ni(%	Co(%)	Cu	Zn^{70}	Ga	Ge	As	Sn^{74}	In	Hg^{76}	Tl	Pb	Bi
Chondrites:															
Ordinary	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Average^{61}	70	0.32	1.34	0.08	90	60	5.0	7.6	0.3	0.43	0.001	0.1	0.001	0.15	0.003
Enstatic															
Abee	163	0.49	2.0	0.08	100	730		29		0.88	—	0.004^{25}	0.096^{25}	3.5^{25}	0.08^{25}
Hvittis	48.6	0.2	1.96	0.07	110	16	—	38.1	—	—	—	—	—	5.0	0.1
Carbonaceous															0.1
Murray	—	0.29	—	0.046	116	—	—	17.3	—	1.05	—	—	—	4.6	—
Migei	—	—	—	—	—	—	—	—	—	—	0.07	—	0.097	1.5	0.18
Achondrites (Feldspar-free):															
Diogenites															
Johnstown	—	0.32	0.03	—	—	3	—	—	—	—	—	0.12	0.0007	—	0.0003
Feldspatic achondrites:															
Howardites															
Pasamonte	—	—	—	—	—	2	—	—	—	—	—	—	—	—	—
Sioux Country	—	—	—	—	—	2	—	—	—	—	—	—	—	—	—
Eucrites	—														
Nuevo Laredo	—	0.1	—	—	—	—	—	—	—	—	—	0.08	0.0008	0.68^{71}	0.0001
Pallasites															
Olivine	17	—	—	—	4	—	—	2	—	—	—	—	—	—	—

	Metallic phase	*Silicate phase*	*Sulphide phase*	
Brenham	0·8	0·6	0·1	Sn
	57·0	0·85	13·3	Gie
Admire	2·35	0·5	0·1	Sn
	30·0	0·63	11·1	Gie

Gallium has less siderophilic character than germanium but is distributed in the same order (p.p.m.)

Silicate phase	3·2
Metallic phase	15·0
Sulphide phase	12·0

According to their gallium and germanium contents meteorites are divided into several groups[69]

	Gallium	*Germanium*	
Group I	80·0–100	300–420	(p.p.m.)
Group II	40 – 65	130–320	
Group III	8 – 24	15–80	
Group IV	1 – 3	1–1	

However, various types of iron meteorites also fit into these groups. The other microcomponents (platinoids etc.) behave similarly. Indium and cadmium, as well as thallium, bismuth, lead and zinc accumulate in FeS_n and their contentrations in carbonaceous and enstatitic chondrites are considerably higher, for instance in the iron meteorite Sikhote-Alin (in%):

	Indium	*Cadmium*	*Arsenic*
Metallic phase	$0{\cdot}3.10^{-7}$	$1{\cdot}6.10^{-4}$	$1{\cdot}8.10^{-3}$
Sulphide phase	$2{\cdot}1.10^{-7}$	$<1{\cdot}6.10^{-3}$	$1{\cdot}5.10^{-4}$

Finally mention should be made of mercury and chromium. Mercury is on average present in higher concentration in ordinary meteorites than in carbonaceous and enstatitic ones. Chromium gives chromites of various compositions[61] as well as daubreelite, $FeCr_2S_4$. These phases have been little studied.

In consequence the following may be said about the distribution of all heavy elements in various types of meteorites. Among FeS_n-rich chondrites carbonaceous and enstatitic chondrites contain more of the chalcophilic elements indium, thallium, bismuth, lead, cadmium, zinc and germanium than do other chondrites. All achondrites (containing little of the metallic phase and FeS_n) contain the smallest amounts of siderophilic and chalcophilic elements. The content of other elements, for instance of tantalum, is higher in chondrites (0·022 p.p.m.) than in achondrites (below 0·01 p.p.m) *etc*. All calcium-rich feldspathic achondrites are richer in strontium, barium, rare-earth elements, thorium and zirconium.

Mercury shows great variation in concentration. It is interesting that olivine from pallasites contains the least amount of these elements.

Finally some words about platinoids and also gold and silver in meteorites. All platinoids (for osmium there are no reliable determinations) are present mainly in the metallic phase and this concentration in the sulphide phase is generally quite small[77, 78].

Iron meteorites and the iron phase of stony meteorites scarcely differ in their content of platinoids. The platinoid content in chondrites is considerably lower, and that in achondrites which do not have an iron phase, is still less. The same applies to gold and silver (*Table 12*).

Between all platinoids there exists a direct correlation with the nickel content in the metallic phase, with the exception of palladium and nickel, where the correlation is essentially reverse. An attempt had been made to divide all iron meteorites into groups (similar to gallium and germanium groups) according to their content of platinoids.

PRODUCTS OF COSMIC IRRADIATION OF METEORITES

Before proceeding further in our search for the causes of fractionation of meteoritic matter, we must return briefly to its composition and, more precisely, to its content of neutral gases. During their long lifetime in space, amounting to several milliards of years, meteorites are subject, apart from changes in morphological structure and radioactive changes, to nuclear processes due to cosmic irradiation not only with high-energy particles coming from the Sun and solar wind, and even more with penetrating galaxy radiations from other stars. Spallation changes the isotopic composition of such elements as ^{50}V, Sc, ^{40}K, giving rise to new long-lived isotopes ^{26}Al, ^{56}Co, ^{58}C, ^{10}Be, ^{23}Na, ^{54}Mn, ^{46}Sc, Ti, ^{53}Cr, ^{59}Cr, ^{36}Cl and a number of others, and cosmogenic neutral gases appear. The meteoritic material differs from that of the Earth in its content of all these isotopes. The study of all these products has effectively opened up an entirely new field which promises to reveal the history of the chemical on of composition of meteorites over their whole lifetime in space, to throw light on their shapes, on the spectrum, intensity and constancy of cosmic radiation, on their absolute and radiation ages, etc. Especially intensive studies have been made of the distribution in meteorites of the neutral gases: helium, argon, neon, krypton and xenon. Meteoritic matter contains at least three groups of gases of different origin, namely, (*i*) primordial connected with nucleogenesis, (*ii*) cosmogenic and (*iii*) radiogenic (omitting products of spontaneous fission *etc*.). One and the same isotope may form in different processes. For instance the cosmogenic ^{36}Cl forms by spallation and the radiogenic by ^{35}Cl neutron capture. The same is true with argon and xenon isotopes. Owing to the fact that depending on their origin, different isotopes with different strength bonds are retained by the crystal lattice, they may be partly separated chemically[83].

The primordial gases were entrapped by the meteoritic matter at the moment of its condensation at low temperature (possibly below 500° C)

Table 12. Platinoids, gold and silver in meteorites (parts per 10^6)

Meteorites	Au	Ag	Ru	Rh	Pd	Os	Ir	Pt
Chondrites:								
Average (19)[79]	0·22	0·094[81]		0·186[81]			0·41	1·5
Achondrites:								
Aubrites								
Norton County	0·0057	—	—	—	—	—	0·0024	—
Diogenites								
Johnstown	0·0040	—	—	—	—	—	0·01	—
Eucrites								
Pasamonte	0·0025	—	—	—	—	—	0·022	—
Iron meteorites:								
Average (24)[78]	1·35[79]	0·075[82]	9·2	1·47	3·5	—	3·7	11·0
Iron phase of stony meteorites								
Average (5)[78]	1·40[80]	—	6·0	0·98	4·1	—	2·8	8·5
Troilitic phase of iron meteorites								
Canyon Diablo	0·1[79]	—	—	—	—	—	0·002[79]	0·71[79]

and probably at a still elevated gas pressure. The composition of these gases, as might have been expected, corresponds to the isotopic composition of the argon, neon, krypton and xenon found in the Earth's atmosphere. In other words, these same gases were partially liberated during fusion and degassing of the substance of the Earth's crust, which is also meteoritic matter[61, 85]. In isotopic composition these gases are similar to those on the Sun.

The accumulation, for instance, of the heavy gases krypton and xenon in meteorites cannot be understood otherwise than through nucleogenesis. To a first approximation all meteorites can be divided according to their neutral gas content into two large groups. Group I covers meteorites containing predominantly primordial gases, and Group II those which contain cosmogenic and radiogenic gases. No doubt these groups can be further subdivided.

The first group includes carbonaceous chondrites, some ordinary chondrites and some achondrites of different kinds. The second embraces most chondrites, various achondrites and all iron meteorites. By way of example, some of the pertinent data is tabulated (*Table 13*). It is evident from these data that the ratios $^{129}Xe/^{132}Xe$, $^{20}Ne/^{22}Ne$, and $^{36}Ar/^{38}Ar$ are the same as the corresponding ratios for these gases in our atmosphere. However, the absolute amounts of the different isotopes vary over a considerable range; for instance, the contents of krypton and xenon in chondrites and achondrites are of different orders, or else their ratios are very different. It is difficult at present to find an explanation for gas fractionation processes. Of course, gas losses are not excluded, helium being lost most easily, and then argon, while krypton and xenon are the last to be lost. Gas content is higher in the fine-size fraction of chondritic matter. It is higher in the chondrules than in the meteorites as a whole. Their loss is evidently related to impacts, to thermal disturbances of the crystal lattice, which profoundly change the entire structure of meteoritic matter. However, it is surprising that many brecciated chondrites and especially achondrites contain large quantities of these primordial gases, for instance aubrites, ureilites, diogenites.

Regarding the composition of the primordial gases, we may refer to more solar and more terrestrial compositions. The xenon isotopic composition is due to a number of processes: U-238 spontaneous fission, U-235 fission induced by neutrons, *etc.*, and^{129} Xe formed from^{129}I†. This makes it possible to determine the length of the interval between the time of nucleogenesis and the formation of the Earth from the content of ^{129}I and ^{129}Xe in the Reynolds meteorite ($\sim 2 \times 10^8$ years). The dark fragments of chondrites contain primary gases, the light ones contain none, etc. We have conventionally placed enstatitic chondrites in the second group of chondrites, achondrites and iron meteorites, though their $^{129}Xe/^{132}Xe$ ratio is the highest. In this sense they are transitional between the two gas groups. *Table 14* shows the $^{20}Ne/^{22}Ne$, $^{36}Ar/^{38}Ar$ and other ratios in chondrites, achondrites and iron meteorites; those constituting the bulk of meteorites differ considerably

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† Principally accumulated in the sulphide phase. The ^{129}Xe excess is accounted for by the high ^{129}I content in the meteorite. ^{136}Xe a product of ^{238}V and ^{244}Pn fission. See Tills about the solar wind as a noble gas source in meteorites. However, some scientists do not bring ^{129}Xe into connection with iodine and tellurium.

Table 13. Meteorites containing predominantly primordial gases (rich in gases)

Meteorites	10^{-8} cc STP/g										$^{129}Xe/^{132}Xe$	$^{20}Ne/^{22}Ne$	$^{36}Ar/^{38}Ar$	Age K-A × ^{9} years	*Reference*
	^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{84}Kr	^{132}Xe					
Carbonaceous chondrites:															
Mighei	2	3700	13	0·65	2·2	62	11·5	850	0·92	1·0	1·09	8·3	5·4	2·4	86, 87
Orgueil	7·7	24800	47·3	0·90	5·1	67	12·0	400	0·90	1·0	1·08	4·3	5·6	1·3	88, 87
Average for six carbonaceous chondrites	—	—	—	—	—	—	—	—	—	—	1·08	9·1	5·4	—	
Chondrites rich in gases:															
Fayetteville	718	$2 \cdot 10^{6}$	28400	111	2650	346	—	—	0·41	0·112	1·25	10·7	5·04	—	91
Pantar	54	149000	179	1·42	15·4	11·1	2·27	4530	—	0·009	1·0	12·4	5·7	3·8	6, 86, 90
Achondrites rich in gases:															
Staroje Pesyanoe	220	630000	2080	23	184	148	27·6	2700	0·06	0·008	1·0	11·3	5·0	4·4	34, 88, 90, 87
Kapoeta	55	205000	2220	7·5	166	88	17·0	1140	0·02	0·006	1·0	13·9	5·2	4·4	87, 91, 98
Earth's atmosphere:	—	—	16·3	0·047	1·6	31·0	5·8	—	0·57	0·02	0·98	10·2	5·35	—	

Table 14. Meteorites containing predominantly cosmogenic and radiogenic gases (depleted in gases)

Meteorites	10^{-8} cc STP/g										^{129}Xe/^{132}Xe	^{20}Ne/^{22}Ne	^{36}Ar/^{38}Ar	Age K-Ar × 10^{9} years	*Reference*
	^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{84}Kr	^{132}Xe					
Ordinary chondrites															
Elenovka	52	1700	7·04	7·30	8·05	5·50	1·70	4800	—	0·08	1·06	0·87	3·3	3·9	Author
Saratov	36	1770	7·04	7·17	7·39	5·40	1·66	3900	—	0·11	1·07	0·96	3·2	3·2	do.
Sevrukovo	6·7	580	6·9	2·35	7·54	22·0	4·20	3460	—	0·13	1·35	0·9	5·0	3·5	do.
Average for ordinary chondrites (28)	—	—	—	—	—	—	—	—	(0·03)	(0·05)	1·0	0·93	1·7	—	do.
Enstatite chondrites															
Abee	12	1320	10	2·5	3·3	37·2	6·9	6900	0·15	0·08	6·4	3·0	5·4	4·7	87
Indarch	13	1270	7·7	3·6	4·5	6·3	1·6	5620	0·04	0·07	4·0	1·7	4·0	4·3	87
Various achondrites															
Pena Blanca	117	1160	21·3	21·5	25·6	0·8	0·7	950	—	—	—	0·84	1·1	3·14	90
Johnstown	49	610	8·2	8·1	8·9	0·55	0·7	67	—	—	—	0·92	0·8	4·32	90
Podvarninkai	—	250	3·7	1·9	1·6	0·9	1·0	359	—	—	—	2·3	0·9	1·0	97
Iron meteorites															
Toluca	100	295	0·8	0·8	0·85	1·7	2·4	15	—	—	—	0·94	0·71	—	98
Canyon Diablo	4·2	42	0·11	0·11	0·11	0·27	0·44	16·7	—	—	—	1·0	0·62	—	
Odessa	220	710	2·4	2·3	2·4	7·0	12·0	10·1	—	—	—	1·0	0·6	—	98
Earth's atmosphere	—	—	16·3	0·047	1·6	31·0	5·8	—	0·57	0·02	0·98	10·2	5·37	—	—

from the corresponding ratios of the neutral gases of the atmosphere, this being especially true of iron meteorites, which have lost their primordial gases.

As is well known, cosmogenic gases and other isotopes are a result of spallation processes. To a certain extent, or course, their composition depends on the composition of the meteorites. These processes have been modelled in accelerators with an iron meteorite as the target[101]. But the share of these gases in meteorites is surprisingly small compared with that of the primary gases, especially if account is taken of the enormous lifetime of meteorites in outer space. The composition of these gases, *viz.*, the ratios ^{3}He/^{4}He, ^{38}Ar/^{39}Ar, and others, made it possible to determine the time of exposure of the meteoritic matter to cosmic irradiations, neglecting the very probable losses of these gases[83, 102]. In other words, according to a number of investigators, this radiation age gives the time of disintegration of smalll cosmic bodies, because space irradiation can affect them only to a small depth of about 40 cm. For instance, no ^{26}Al, or ^{10}B was found in the Canyon Diablo. The protective irradiated layer burned in the Earth's atmosphere, while the deeper layers of the meteorite were not affected by irradiation. Such radiation ages are listed by way of example in *Figure 17.* The radiation age of various chondrites and achondrites fits more or less compactly in the age range of 20–40 × 10^{6} years and 4 × 10^{6} years in the case of bronzitic chondrites.

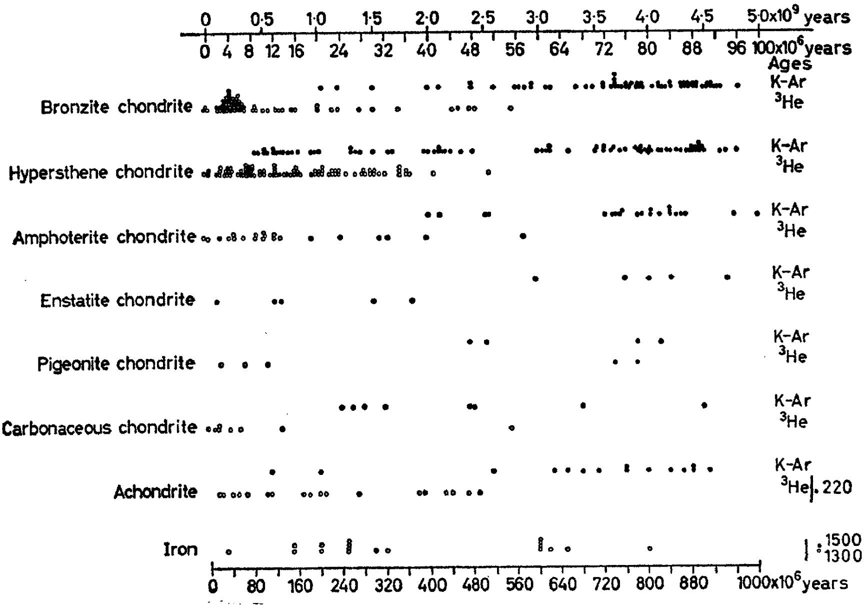

Figure 17. The absolute and cosmic age of meteorites. The absolute K/Ar age (upper scale) is marked by black dots, the cosmic age (lower scale) by circles. The scale for the cosmic age of iron meteorites is given at the bottom[5, 34, 47, 98, 103–105, 143]

The hypersthenic chondrites show a greater spread. For coarse octahedrites the age is about 9 × 10^8 years and for octahedrites with medium structure it is ~ 6·5 × 10^8 years; but this may be due to insufficiency of statistical data.

There have been attempts to relate these "peak" ages to various cosmic events. For instance it is assumed that the iron meteorite Canyon Diablo was detached from a cosmic body 540 × 10^6 years ago, but was crushed ~ 170 × 10^6 years ago. It is surprising that iron meteorites, which according to many scientists were concealed inside the cosmic bodies, and therefore disintegrated last, have a radiation age considerably higher (80 × 10^6 to 800 × 10^6 years) than stony meteorites. Finally, the content of radiogenic radioactive decay products, *i.e.*, U, Th, ^{40}K ^{4}He, ^{40}Ar, as well as lead isotopes, have made it possible to determine the absolute age of meteorites and the time of their solidification in one way or another. The argon–potassium age of meteorites is shown in *Figure 17*. These values are slightly higher than the ^{4}H and ^{3}T ages. Apparently the best results are obtained by the ^{87}Sr/^{87}Rb method and by the lead–lead method[†].

It is not possible to dwell on this question of absolute age. The absolute age of the dark matter of stony meteorites is higher than that of the light matter in the same fragment. The general tendency is towards an age of 4–5 × 10^9 years, which we have to admit as the initial age of chemical differentation of meteoritic matter. This is also an indication of possible gas losses in some meteorites. Considerable scattering is observed in the case of achondrites and small ages are observed for carbonaceous chondrites, which are more likely to lose Ar. As a rule the rubidium–strontium, lead–lead and argon–potassium methods show ages approaching 4–4·5 × 10^9 for iron-meteorites.

DOES THE METEORITE COMPOSITION REFLECT THE COMPOSITION OF THE METEORITE BELT MATERIAL?

Now that we have an idea of the great variety of compositions of different meteorites and are about to turn to the processes which resulted in fractionation of meteoritic matter, I should like to draw your attention for a few moments to the types and masses of the meteorites that predominantly fall on Earth, in order to give a correct idea of the true composition of the meteoritic matter revolving about the Sun and intersecting the orbits of Earth and Mars, and to compare its composition to that of the Earth, other planets, and the Sun.

It is evident from *Tables 15* and *16* that 1759 meteorites have been collected up to the present time in museums, but it must be pointed out that the number of meteorite finds is greater than the number of meteorite falls.[‡] The falls are predominantly stony meteorites, while the finds are predominantly iron meteorites. This is easily accounted for. Iron meteorites keep excellently

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[†] See Pinson's a.o. data on rubidium–strontium methods of chondrite age determination and Hess' a.o. data on the lead–lead method for stony meteorites. They have practically given similar results (above 3 × 10^9 to 4·5 × 10^9 years).

[‡] A statistics of falls by seasons[12, 109] according to unification of meteorites into geographical groups[110, 111].

Table 15. Number of stony meteorites (in January 1965)

Meteorite	*Number of falls*	*Number of finds*	*Total*
Chondrites			
Olivine	3	1	4
Bronzite	62	21	83
Hypersthene	131	33	164
Carbonaceous	23	—	23
Enstatite	15	4	19
Amphoterites	9	1	10
Unclassified	353	263	616
Total	596	323	919
Achondrites (feldspar-free)			
Aubrites	6	1	7
Ureilites	2	1	3
Diogenites	5	—	5
Nakhlites	1	1	2
Angrites	1	—	1
Chassignites	2	—	2
Total	17	3	20
Achondrites (feldspathic)			
Eucrites	15	3	18
Shergottites	1	—	1
Howardites	14	2	16
Total	30	5	35
Unclassified achondrites	3	3	6
Usual achondrites	50	11	61
Unclassified stony meteorites	58	44	102
Usual stony meteorites	704	378	1082

Table 16. Stony-iron and iron meteorites (in January 1965)

Meteorites	*Number of falls*	*Number of finds*	*Total*
Stony-iron meteorites			
Pallasites	3	40	43
Siderophyres	—	1	1
Lodranites	1	—	1
Mesosiderites	8	12	20
Unclassified stony-iron meteorites	3	11	14
Usual stony iron meteorites	15	64	79
Iron meteorites			
Hexahedrites	6	45	51
Ataxites (nickel-poor)	1	24	25
Octahedrites (coarse)	7	108	115
Medium octahedrites	13	179	192
Fine octahedrites	4	78	82
Breccias	2	12	14
Ataxites (nickel-rich)	—	39	39
Unclassified iron meteorites	5	21	26
Usual iron meteorites	45	553	598
Usual meteorites	764	995	1759

in the Earth, while stony ones disintegrate in time. For instance, no carbonaceous meteorite has been found. Possibly, the total number of falls of stony meteorites is, in general, greater than of iron ones. The first place among stony meteorites both in falls and finds is held by chondrites (particularly, hypersthenic). These constitute 84 per cent of all finds and falls of stony meteorites. As we shall see, the number of cases of other stony meteorites is incomparably smaller and some are solitary cases. Many meteorites have still to be studied (44 per cent) and about 100 of them have not yet been classed. However, on the other hand, the total mass of all stony iron meteorites is much larger than that of all known stony meteorites.

Indeed, the total mass of only the four largest meteorites on Earth, *i.e.* the Hoba (Africa), the Canyon Diablo (U.S.A.), the Sikhote-Alin (U.S.S.R.) and the Cape York (Greenland) amounts to thousands of tons, while stony meteorites seldom have a ton mass (only the Norton County). More frequently large falls and meteorite showers constitute hundreds of kilograms and, in most cases, much less. Probably stony meteorites split more easily on collision in space. However the absence of large fragments of stony meteorites cannot be attributed to pulverization of these loose meteorites in the Earth's atmosphere, because the stony meteorite fragments formed by crushing in the atmosphere can afterwards easily be reconstructed into a single pre-atmospheric monolith. Our planet is 40 per cent iron alloy and 60 per cent silicate phase. The ratio in other terrestrial planets is about the same.

Thus, we have the alternatives: (*i*) we assume that the average composition of the meteorites that have come into the hands of man corresponds to that of the meteorites existing in our solar system, or (*ii*) we assume that the composition of the meteorites that have fallen on the Earth (as well as on the other planets) is of a selective nature (and therefore changes in time) and does not represent the average composition of the meteorites in outer space. If we accepted the first assumption then as long as there are on Earth single meteorites of special composition, such as chassinyites, angrites, sherghottites, siderophyres, lodranites, *etc.*, we should have to be constantly changing our ideas of the composition of meteorite matter. As only chondrites are closer then the others to the average composition of the Sun[62], we must accept the second assumption that meteoritic falls are selective in nature.

ORIGIN OF METEORITES

Now we come to the question of the processes which caused fractionation of meteoritic matter. The idea that chondrites are frozen droplets of silicates was suggested as far back as last century. However, many other hypotheses were put forward at the same time concerning the method of formation of chondrules, associated primarily and mainly with the idea of the existence of small cosmic bodies (moons) or asteroids, on whose surfaces chondrites and other meteorites originated as a result of volcanism or hypothetical spheroidal crystallization[21, 147]. It should be noted that volcanic bombs and lapilli are saturated with common gases, have gas bubbles *etc.*, which has never been observed in chondrites. Coalesced dumb-bell shaped, oval and lipped chodrules are encountered, resembling drops of glass and other frozen liquids. These silicate drops can be obtained experimentally from low-temperature plasma. During explosions of atom bombs in underground caverns, similar solid spherules of various sizes are formed (ranging from fractions of 1 Å and larger). Their size depends on the power of the explosion and the ballast of the bomb. The more powerful the explosion, the more heat is generated, and the smaller are the spherules. Hence, the size of the chondrules bears evidence of the regions of their condensation with respect to the Sun. Thus at a temperature of ~ 5·000°C or lower, solar plasmic matter is partly transformed into solid frozen silicate spherules as a result of abrupt cooling over a very short period, *e.g.* a few seconds. Condensation did not occur from the vapour (as some investigators believe), but through the formation of liquid drops. Chondrules contain glass and they are spherical in shape. This is sufficient evidence of their previous liquid spheroidal state. They are solid and have no concentric layers like hailstones, Besides, condensation into a solid chondrule directly from the vapour is impossible since this process would result in the formation of crystal (growth dendrites). The silicate matter has a high evaporation and melting point, especially olivines (> 1800°C and higher). Possibly, under certain conditions these drops underwent repeated recondensation and were thus "purified" from their more volatile impurities, *e.g.* olivinic and other chondrules (especially the "pure" ones, as we have seen in pallasites, *etc.*) which promoted some fractionation of the silicate chondrules[113].

Chondrules are found in achondrites too, for example, in ureilites, howardites and even in the form of fragments in stony iron meteorites, mesosiderites. The chondrules in many chondrites underwent recrystallization after some time to form a variety of structures of crystalline chondrites. The transformation of chondrules may be a much more complex process, and chondrules are sometimes completely transformed into crystalline aggregates. This can be seen in the fine patterns of chondrites and achondrites left over by the former chondrules. Experiments show that at temperatures above 1·000°C chondrules disappear rather quickly, and at about 500°C and 10·000 atmospheres the chondrules disappear in a short time[61]. Thus, the substance of chondrites doubtlessly participated in the composition of achondritic meteorites. The disappearance of the chondrules in the course of their metamorphism suggested that achondrites might have originated in this way, but this idea is insufficiently substantiated without some knowledge of the changes in chemical and mineral composition. Chondrule formation is followed by agglomeration of chondrules with a different history of formation. Probably these agglomeration processes, accompanied by collisions, crushing and loss of chondrule matter, occur under various conditions in various areas of the cloud fields as a result of which a certain variety of composition is found among chondrites, *i.e.*, volatile-rich carbonaceous enstatic and ordinary. The various brecciated structures of meteorites suggest the occurrence of collision processes. Every meteorite fragment had undergone multiple impacts.

Agglomeration and chemical processes with various forms of iron, the condensation of which proceeded independently of the condensation of the silicate matter, occurred locally in the cooled cloud. That was how the three genetically related families of chondrites (carbonaceous, enstatitic and ordinary chondrites) which were rich and poor in primary gases, were formed; but taken together they all represent a single type of change of the primary matter.

Carbonaceous chondrites could not have been primary matter from which all other chondrites and achondrites had formed. Their mass is probably very small. Their composition does not correspond to the composition of the Sun. Their formation is connected with local agglomeration processes in the cooling cloud containing much volatiles—H_2O, C, S.

Chondrites could not have been fragments of any large cosmic body, because if they had, the chondrules would have disappeared owing to the pressure. They could not have been the outer shells of small cosmic bodies, because differentation of these bodies into shells (which is considered necessary to account for the origin of the "achondrite" layers) would have resulted in fusion and degassing from the interior parts of the body, so that the more easily fusible fraction appeared on the surface, etc.

The interrelations in the achondrite group are still more complicated, and are far from clear. Part of the achondrites are to a certain extent close to chondrites in nature, in composition and even in content of rare chondrules; such, for instance, are ureilites and perhaps diogenites. Possibly, enstatitic achondrites (aubrites) will turn out to be related as regards their history, to enstatitic chondrites. Another group, that of naclites angrites, and chassinyites, stands quite apart owing to their peculiar composition. Finally, feldspathic achondrites or eucrites proper (the rest of the polymict breccias) constitute a third group. Among achondrites, like chondrites, we find meteorites with a high content of the volatile fraction and with the original neutral gas composition. It has already been mentioned that a high content of the original neutral gases is not infrequently associated with brecciated structure in achondrites (*e.g.* with howardites). This is another unsolved question.

Some investigators assume that achondrites may have been formed from chondrites as a result of metamorphosis of the latter. Obviously this may be true, to some extent, of only certain feldspar-free achondrites, ureilites, enstatitic and hypersthenic achondrites. But even so, the concept of metamorphism must be extended, because in this case these possible transformations involve a loss of chondrite matter (iron, FeS_n, trace elements) in consequence of heating, oxidation, *etc.* In other cases these transformations are still more profound and are connected with a change in composition, and possible increase in matter, in feldspathic achondrites. In the last case the transformation of chondrites into aluminium- and calcium-rich achondrites can only be thought of as a process of selective fusion of chondrite material. We have to bear in mind that feldspars are unstable at high temperatures and pressures[112]. Where could this process have occurred, if it did? The answer to this question is clear if we remember that achondrites are not infrequently similar to basic rocks on Earth, *i.e.* diabases, eucrites, or to the matter of the Earth's crust, *i.e.*, olivine with chromites in chassinyites, *etc.* Hence, such achondrites must have passed through the planetary stage and been formed as a result of fusion during the differentiation of the substance of a cosmic body of the size of the moon. In other words, they went through a magmatogenic process. Evidently, if we accept this explanation, this process can refer only to quite definite achondrites, excluding meteorites which contain primary gases and so on, *i.e.* primarily, to eucrites, or perhaps naclites or angrites or chassinyites. Perhaps this is why so few of these meteorites of peculiar composition fall on the Earth, if this process of *fusion* on lunar bodies is so rare a phenomenon.

Thus, for lack of anything better, we must assume by way of hypothesis that for a limited group of achondrites, the method of formation differed from that of chondrites in the passing through the planetary stage.

The cosmic history of iron is a key question. During cooling of solar matter iron condensed as a metallic alloy. The assumption that the primary form of condensation was ferrous oxide which was reduced later by hydrogen or other gases, is not acceptable because, if this were the case, there could not be such large amount of nickel, cobalt, platinum, germanium, galium and other impurity elements present in the metallic iron. By reason of metamorphism, these elements could not have been present together with the ferrous oxide, as we have now found in the metallic alloy of meteorites. It is inconceivable that all these elements were isolated from the meteoritic matter by liquid iron. Moreover, iron condensed separately and independently of the silicate component in the form of an iron shower, as Euken figuratively put it, though with a different purpose dissolving impurity elements giving solid solutions with iron.

This idea of the separate condensation of iron has been referred to many times[61, 113]. Thus pallasites are either a result of incomplete differentiation of matter into the silicate phase and the metal, say, in a gravitational field, or, conversely, are the result of agglomeration of silicate matter with iron (*Figure 18*). Otherwise, how can we account for the formation of mesosiderites containing polymict breccia in their silicate phase? The answer is only by agglomeration. Iron condensed from the vapour into a liquid. In chondrites and other meteorites (Renazzo, Groznaya) we find round solidified drops of iron. It is not impossible that iron condensed from the vapour directly into the solid form. But proceeding from the iron equilibrium at the triple point, it may be thought that the region of direct transition of iron from vapour to solid is very narrow and involves a very high vacuum. This process should have resulted in the growth of iron dendrites. In this connection it is interesting to point out the shape of the irregular fragments of the FeNi phase in stony meteorites. Thus agglomeration of iron in heterogenous silicate matter has led to the formation of various stony iron mixed meteorites.

Cloud condensation of iron involved interaction with oxygen, hydrogen sulphide and silicate matter. To account for the variety of ratios between silicate, metallic and sulphide iron in chondrites, at least, we must imagine the complex local situations in solar matter, the simultaneous and intensive interaction between the silicate matter (chondrules), and various iron compounds and gases, as a result of incessant collisions, gas shock waves and cosmic radiation. This resulted in the variety of iron/silicate phase ratios found in meteorites. The proper iron meteorites show signs of repeated impacts, FeS_n plate deformation *etc*. Finally, we come again to the same question that arose in connection with the history of achondrites. Did meteoritic iron (iron–nickel meteorites) pass through the planetary stage, *i.e.*, after being agglomerated by the substance of a cosmic body which had reached the size of a lunar cosmic body, did it again become fused into an iron core as a result of separation of this body into shells? And then as a result of the collision of at least two bodies, did it return again to the life of an iron meteorite? It seems to me that what we have learned about iron meteorites gives grounds for believing that this hypothesis of the secondary fusion of Fe in the depths of lunar bodies may be disregarded. In any case signs of this secondary fusion must be displayed.

PROBLEMS OF COSMIC CHEMISTRY IN THE IMMEDIATE FUTURE

In conclusion it must be said that the composition of chondritic meteorites is closest of all to that of the revolving layer of the Sun. According to the absolute age determined for meteorites (and the Earth), *i.e.* between $4{\cdot}7 \times 10^9$ and $5{\cdot}0 \times 10^9$ years, the proto-sun ejected an immense mass of hot plasmic matter, which formed a ring in the equatorial plane of the Sun.

Thus temperature and pressure were high only at the beginning of meteoritic life. As this plasmic cloud grew cooler, at a temperature below 5000°C and at considerable vapour density, the matter began to condense into liquid silicate drops (chondrules) and separately into an iron–nickel alloy. Owing to the unsteady state of rotation, the proto-solar ring broke up, as it cooled down, into a number of condensed phases which resulted in the formation of Earth-type planets, while part of the condensed matter remained scattered in the so-called meteoritic belt of our system as chondrules and agglomerations of chondrules with iron–nickel alloy into meteorites.

Thus, chondrules originated directly from the plasmic matter of the Sun prior to the meteorite and planetary stage, and are not products of any such process as magmatic differentiation. They are the most widespread primitive state of matter. The composition of the chondrules was chemically fractionated in the course of their formation by recondensation of the chondrule substance and, by loss of volatiles to the cosmic vacuum in the course of cooling, *etc.* Finally, owing to incessant collisions between bodies of different sizes, shapes and composition, these bodies were split, crushed, abraded, *etc.* The simultaneous process of agglomeration of this diverse matter also promoted the formation of the different types of meteorites, in particular, brecciated meteorites which are a mixture of fragments having different origins. Chondrites, which are agglomerations of chondrules cemented with fragments and dust, also of chondrule origin, are multiphase non-equilibrium systems. Chondrule matter was the chief material from which all the other types of meteorites were formed.

There are no indications of the influence of high temperatures or high pressures on the transformation of chondrites into achondrites. Chondrites are bodies of low density, which are found in the absence of any considerable gravitational field. The phase transformations in all types of meteorites show no evidence that the temperature was higher than 400 or 500°C. Chondritic matter bears signs of a lengthy existence, in particular, under conditions of cosmic irradiation and high vacuum.

As we have seen, it is very probable that some types of achondrites might have originated from small chondritic aggregations with loss of certain substances in vacuum.

Some achondrites, namely basaltic and certain others rich in calcium oxide, alumina, strontium, barium, thorium, zirconium and rare-earth elements[†] may possibly have undergone subsequent planetary evolution, *i.e.* may have arisen a second time on small cosmic bodies (lunar bodies) owing to differentation of the latter into shells due to the heat of radioactive decay, and subsequent break-up of these lunar bodies or asteroids as a result of collisions. This hypothesis requires further development and neither can the percentage of chondritic matter that followed this planetary path be determined. It may be thought that the iron fraction in iron meteorites avoided it. There are still not only very many contradictory opinions, but also very many contradictory facts regarding meteorites. It is now the task of the physical chemists who have been working intensively at this problem, especially in recent years. There are reasons to think however that further knowledge of meteoritic matter will make it possible for us to discover the history of our galaxy.

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