Kirk-Othmer Encyclopedia of Chemical Technology.

EXTRATERRESTRIAL MATERIALS

Extraterrestrial materials are samples from other bodies in the solar system that can be studied in Earth-bound laboratories. Sensitive and ever-improving analytical techniques are used to provide information at levels of detail and sophistication that cannot be matched by telescopic or spacecraft investigations (see Analytical methods). Much of the knowledge of early solar system bodies, processes, environments, and chronology has come from the study of these samples. Extraterrestrial materials that are available for laboratory study include meteoritic materials that fall naturally to the Earth, some meteoritic material that has been captured in space, and lunar samples that were recovered by the Apollo and Luna sample-return missions flown to the Moon during the years 1969 to 1972 (1). Missions to return samples from Mars, asteroids, and comets have been studied but have never been successfully implemented. The meteoritic materials in existing collections include samples from asteroids, comets, the Moon, and probably Mars. The comet and asteroid samples are the best preserved solids from the early solar system and are the oldest and most cosmochemically primitive samples available for direct study. Because of the primitive and unfractionated nature, these samples provide the best determination of the composition of the Sun and the solar system as a whole. It has been shown that many meteorites contain preserved interstellar grains, particles older than the Sun that formed around other stars and served as the initial building blocks of the solar system.

1. Meteorites

Meteorites by definition are extraterrestrial materials that fall from the sky and actually hit the surface of the Earth. In space they are considered to be meteoroids and during their luminous entry into the atmosphere they are called meteors. Meteorite strictly applies only after impacting the Earth. Conventional meteorites are rocks ranging in size from a centimeter to a few meters. The largest known meteorite is the 70-ton Hoba that resides at its discovery site in South Africa. Larger meteoroids do not sufficiently decelerate from cosmic velocity in the atmosphere and are destroyed upon impact, forming an explosion crater. Meteorites fall randomly to Earth but are not found randomly distributed on the Earth's surface. The highest general concentrations of meteorites occur in Antarctica where long exposure time and the combined effects of ice movement and sublimation concentrate meteorites on top of blue ice fields. Because of the scarcity of country rocks, it has been possible to collect over 10,000 meteorites from Antarctica since the early 1970s. In Antarctica and elsewhere, meteorites are often found in clusters created by the breakup of a larger body during hypervelocity entry into the atmosphere. When a meteor breaks up at high altitude, the resulting fragments impact over an elliptical region several kilometers across the ground, forming a strewn field where sometimes thousands of individual specimens are found. Because of atmospheric breakup, the number of individual meteorite specimens that are collected is much larger than the actual number of meteoroids that produced them. Meteoroids are themselves fragments of bodies that broke up in space, and the actual lineage of meteoritic samples may trace back to a relatively limited number of initial parent bodies.

Table 1. Meteorite Classification

Meteorite type	Class	Frequency of occurrence,[a] %
chondrites	CI	0.7
	CM	2.0
	CV	1.1
	CO	0.8
	CR	<0.5
	H	32
	L	39
	LL	7.2
	E	1.5
achondrites	aubrites	1.1
	urelites	0.4
	howardites	1.1
	diogenites	2.4
	eucrites	2.7
	lunar	<0.5
irons	all types	4.7
stony irons	pallasites	0.3
	mesosiderites	0.8

[a]Percentage of meteorites seen to fall.

All meteorites enter the atmosphere at velocities in excess of 11.2 km/s, the velocity of escape from the Earth. For the kilogram bodies that produce most meteorites, the high initial kinetic energy of $>10^8$ J/kg (2×10^7 cal/kg) is lost in only a few seconds time scale by collision with air molecules in the 100–30 km altitude range (2). During the period of deceleration to a terminal velocity on the order of 100 m/s, a meteoroid undergoes fragmentation resulting from mechanical and thermal stress. It also loses a significant fraction of its original mass by ablation. The ram pressure of atmospheric air is high and only strong materials survive without fragmentation into dust. The resulting selection process prevents weak meteoroid types from becoming meteorites. This process prevents the fragile matter observed in the annual cometary meteor showers from producing conventional meteorites. In many cases, the thermal effects of atmospheric entry results in ablation of more than half of the initial meteoroid mass. Because of the short duration of atmospheric heating, the heat pulse penetrates only a short distance into the surviving meteorite mass. All freshly fallen stone meteorites have a glassy fusion crust a few 100 μm thick. In general, discernible thermal effects rarely penetrate more than a few millimeters.

1.1. Types

Most meteorites can be classified into definite groups distinguished by elemental, mineralogical, petrographic, and isotopic composition (3). The general groups are the chondrites, achondrites, irons, and stony irons (Table 1). Although fragments of one meteorite class are often found inside another as a result of collisional mixing, in general the bulk properties of meteorites fall into quantified groups without a continuum of compositions between established groups. It is likely that some groups are samples of single asteroids, the apparent source of most meteorites. The majority of asteroids are located in the asteroid belt between Jupiter and Mars, and are believed to be relic solar nebula planetismals that escaped incorporation into planets. It is not known if asteroid compositions are quantized or if there is actually a continuum of compositions and the existing meteorites are just an incomplete sampling of a broader population. Comparison of spectral reflectance data from laboratory meteorites with that from asteroids indicates that meteorites are not a representative sampling of the asteroid belt (4).

Table 2. Solar System Abundances of the Elements[a]

Element	Solar system[b]	Mean CI chondrite, ppb	Orgueil, ppb	Element	Solar system	Mean CI chondrite, ppb	Orgueil, ppb
H	2.79×10^{10}		2.02	Ru	1.86	712	714
He	2.72×10^{9}		56×10^{3}	Rh	0.344	134	134
Li	57.1	1.50×10^{3}	1.49×10^{3}	Pd	1.39	560	556
Be	0.73	24.9	24.9	Ag	0.486	199	197
B	21.2	870	870	Cd	1.61	686	680
C	1.01×10^{7}		3.45[c]	In	0.184	80	77.8
N	3.13×10^{6}		3.18×10^{6}	Sn	3.82	1720	1680
O	2.38×10^{7}		46.4[c]	Sb	0.309	142	133
F	843	60.7×10^{3}	58.2×10^{3}	Te	4.81	2320	2270
Ne	3.44×10^{6}		203[d]	I	0.90	433	433
Na	5.74×10^{4}	5×10^{6}	4.9×10^{6}	Xe	4.7		8.6
Mg	1.074×10^{6}	9.89[c]	9.53[c]	Cs	0.372	187	186
Al	8.49×10^{4}	8.680×10^{6}	8.69×10^{6}	Ba	4.49	2340	2340
Si	1.00×10^{6}	10.64[c]	10.67[c]	La	0.4460	234.7	236
P	1.04×10^{4}	1.220×10^{6}	1.18×10^{6}	Ce	1.136	603.2	619
S	5.15×10^{5}	6.25[c]	5.25[c]	Pr	0.1669	89.1	90
Cl	5240	70.4×10^{4}	6.98×10^{5}	Nd	0.8279	452.4	463
Ar	1.01×10^{5}		751[d]	Sm	0.2582	147.1	144
K	3770	5.58×10^{5}	5.66×10^{5}	Eu	0.0973	56.0	54.7
Ca	6.11×10^{4}	9.28×10^{6}	90.2×10^{4}	Gd	0.3300	196.6	199
Sc	34.2	5.82×10^{3}	5.83×10^{3}	Tb	0.0603	36.3	35.3
Ti	2400	4.36×10^{5}	4.36×10^{5}	Dy	0.3942	242.7	246
V	293	56.5×10^{3}	56.2×10^{3}	Ho	0.0889	55.6	55.2
Cr	1.35×10^{4}	2.66×10^{6}	2.66×10^{6}	Er	0.2508	158.9	162
Mn	9550	1.99×10^{6}	1.98×10^{6}	Tm	0.0378	24.2	22
Fe	9.00×10^{5}	19.04[c]	18.51[c]	Yb	0.2479	162.5	166
Co	2250	50.2×10^{4}	50.7×10^{4}	Lu	0.0367	24.3	24.5
Ni	4.93×10^{4}	1.10[c]	1.10[c]	Hf	0.154	104	108
Cu	522	1.26×10^{5}	11.9×10^{4}	Ta	0.0207	14.2	14.0
Zn	1260	3.12×10^{5}	31.1×10^{4}	W	0.133	92.6	92.3
Ga	37.8	10.0×10^{3}	10.1×10^{3}	Re	0.0517	36.5	37.1
Ge	119	32.7×10^{3}	32.6×10^{3}	Os	0.675	486	483
As	6.56	1.86×10^{3}	1.85×10^{3}	Ir	0.661	481	474
Se	62.1	18.6×10^{3}	18.2×10^{3}	Pt	1.34	990	973
Br	11.8	3.57×10^{3}	3.56×10^{3}	Au	0.187	140	145
Kr	45		8.7[d]	Hg	0.34	258	258
Rb	7.09	2.30×10^{3}	2.30×10^{3}	Tl	0.184	142	143
Sr	23.5	7.80×10^{3}	7.80×10^{3}	Pb	3.15	2470	2430
Y	4.64	1.56×10^{3}	1.53×10^{3}	Bi	0.144	114	111
Zr	11.4	3.94×10^{3}	3.95×10^{3}	Th	0.0335	29.4	28.6
Nb	0.698	246	246	U	0.0090	8.1	8.1
Mo	2.55	928	928				

[a]Ref. 6.
[b]Atoms per 1.00×10^{6} Si atoms.
[c]Value given is percentage.
[d]Value given is in pL/g.

1.1.1. Chondrites

Over 90% of meteorites that are observed to fall out of the sky are classified as chondrites, samples that are distinguished from terrestrial rocks in many ways (3). One of the most fundamental is age. Like most meteorites, chondrites have formation ages close to 4.55 Gyr. Elemental composition is also a property that distinguishes chondrites from all other terrestrial and extraterrestrial samples. Chondrites basically have undifferentiated elemental compositions for most nonvolatile elements and match solar abundances except for moderately volatile elements. The most compositionally primitive chondrites are members of the type 1 carbonaceous (CI) class. The analyses of the small number of existing samples of this rare class most closely match estimates of solar compositions (5) and in fact are primary source solar or cosmic abundances data for the elements that cannot be accurately determined by analysis of lines in the solar spectrum (Table 2).

Another unique property of chondrites is the presence of chondrules, objects found in nearly all chondrites except those of the CI class. Chondrules (Fig. 1) are millimeter-sized, spheroidal bodies composed predominantly of olivine [1317-71-1], $(Mg,Fe)_2SiO_4$, pyroxene, and a glass of approximate feldspathic composition. The textures of chondrules range from very fine-grained cryptocrystalline to well-formed crystals contained in glass. Chondrule textures of silicate minerals and interstitial glass indicate that these were once molten spherical bodies that cooled rapidly (time scales from minutes to hours) (7). The shape resulted from surface tension acting on small molten droplets freely suspended in the solar nebula. Rapid cooling times indicate local transient heating events in the solar nebula, but details of the origin of chondrules, the source of heating, and the nature of their precursors are very poorly known. It is believed that these were objects individually orbiting the sun formed by rapid heating and cooling of millimeter-sized precursors (7). The processes must have been highly efficient, as chondrules comprise $>75\%$ of the mass of many meteorites. It is possible that chondrules were the primary building blocks of the Earth and the terrestrial planets. The material between chondrules is a fine-grained matrix that has a complementary relationship with chondrules in the sense that it contains an excess abundance of elements such as volatiles and iron in which chondrules are depleted. Although the ratio of chondrules to matrix varies among different chondrites the combined bulk composition is approximately constant. In some chondrites, the chondrules have well-defined rims of fine-grained matrix, suggesting that at least some matrix material directly accreted onto chondrules before the chondrules accreted to form the meteorite parent bodies (8).

Chondrites are divided into eight subclasses distinguished by elemental, isotopic, and mineralogical composition. Seventy-eight percent of falls, meteorites actually seen to fall (eliminating discovery bias), are the H, L, and LL groups that together are termed the ordinary chondrites. The second most abundant group is the carbonaceous chondrites, where the prefix begins with C. The second letter in each carbonaceous chondrite group designates the name of the town nearest to the fall location of the prototypical specimen. For example, the CI and CM classes are named after the CI chondrite Ivuna and CM chondrite Murray, respectively. The rarest of the C chondrites are the CIs. Many of the distinguishing properties of the chondrite classes are the result of fractionation processes that occurred in the solar nebula during or before the time when the meteorites accreted from small grains.

A characteristic distinguishing different chondrite groups is the abundance and oxidation state of iron, Fe. As shown in Figure 2, the Fe:Si ratio of these groups varies by a factor of up to 2, and the oxidation state of Fe varies from totally reduced in the case of E chondrites, to the totally oxidized CI chondrites. The relative abundances of many of the siderophile (iron-loving) elements such as Ni, Co, Ir, and the other elements in Groups 8–10 (VIII) closely follow the iron content. The Fe–silicate fractionation in chondrites is most probably the result of differences in the efficiency in formation and accretion of the silicate and metal grains from which chondrites formed. The variations of Fe oxidation state are related to the temperature at which the solar nebula gas and grains last equilibrated and the regional H_2:H_2O ratio in nebular gas. This ratio strongly influences the condensation of many compounds and determines the oxidation state of Fe in condensed solids. Under equilibrium conditions, Fe condenses above 1000 K as metal from nebular gas having solar H_2:H_2O ratios. It

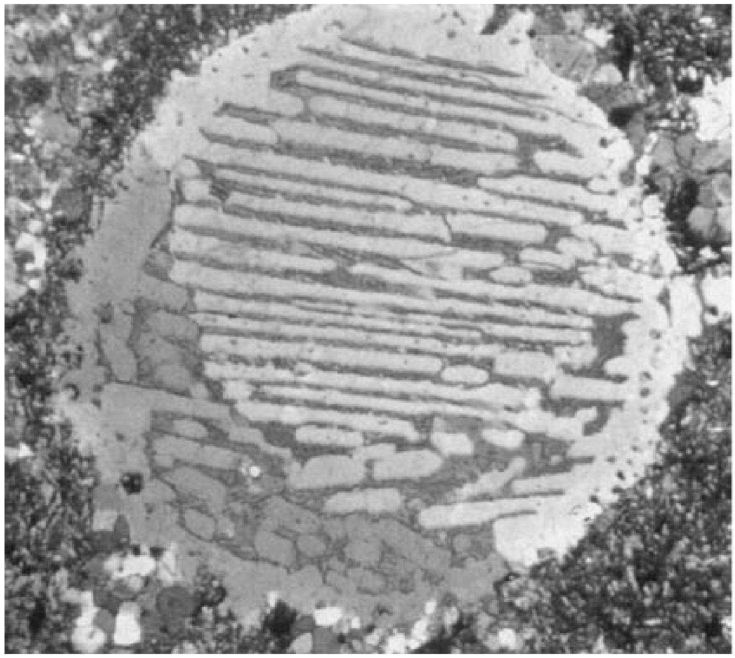

Fig. 1. A "barred olivine" chondrule from the Allende-type CV chondrite that fell in Mexico in 1979. The transmitted polarized light image of the 0.5 mm-diameter chondrule was taken from a polished thin section. The bars are composed of olivine, $(Mg,Fe)_2SiO_4$. The interstitial material is glass quenched by rapid cooling.

forms oxides only at lower temperatures or in environments where the H_2:H_2O ratio is low (9). The H_2:H_2O ratio in the nebula can vary widely owing to concentration of oxygen-rich solids such as ice and silicates followed by subsequent vaporization and enrichment of the surrounding nebular gas.

Chondrite classes are also distinguished by their abundances of both volatile and refractory elements (3). For volatile elements the variation among groups results from incomplete condensation of these elements into solid grains that accrete to form meteorite parent bodies. Volatile elements such as C, S, N, Zn, Cd, Bi, In, and Pb show large and systematic variations between the most volatile rich meteorites, ie, the CI and CM chondrites, and the ordinary chondrites. Refractory elements such as Ca, Al, Ti, Zr, and Sc show remarkably tight clustering in their Si normalized ratios (Fig. 3), with distinct differences between the chondrite classes. If the CI chondrites represent the actual solar-system abundances of these elements, then most of the other chondrites are depleted in refractory elements whereas the CV class is enriched. These elements condense as a group before the condensation of Mg silicates and Fe metal that dominate the mass of stony objects. The compositional variation among different classes is presumed to be related to differing processes of accretion. The earliest solids to condense in the solar nebula were composed of refractory elements. If these solids preferentially accreted into certain bodies or were otherwise separated from the remaining nebular materials, then later-forming objects would accumulate from reservoirs depleted in refractory elements. Examples of the first generation of refractory condensates (or evaporative residues) are found in carbonaceous chondrites as calcium–aluminum-rich inclusions (CAIs). These inclusions range in size from tens of micrometers to several centimeters in diameter and are dominated by refractory silicates and oxides such as melilite [12173-94-3], perovskite [9003-99-0], spinel [1302-67-6], diopside [14483-19-3] and hibonite. CAIs have very low initial ^{87}Sr:^{86}Sr ratios, implying formation in the earliest history of the solar system (10), and contain isotopic anomalies owing to the presence of presolar components and the decay of extinct isotopes such as ^{26}Al (11). CAIs are most

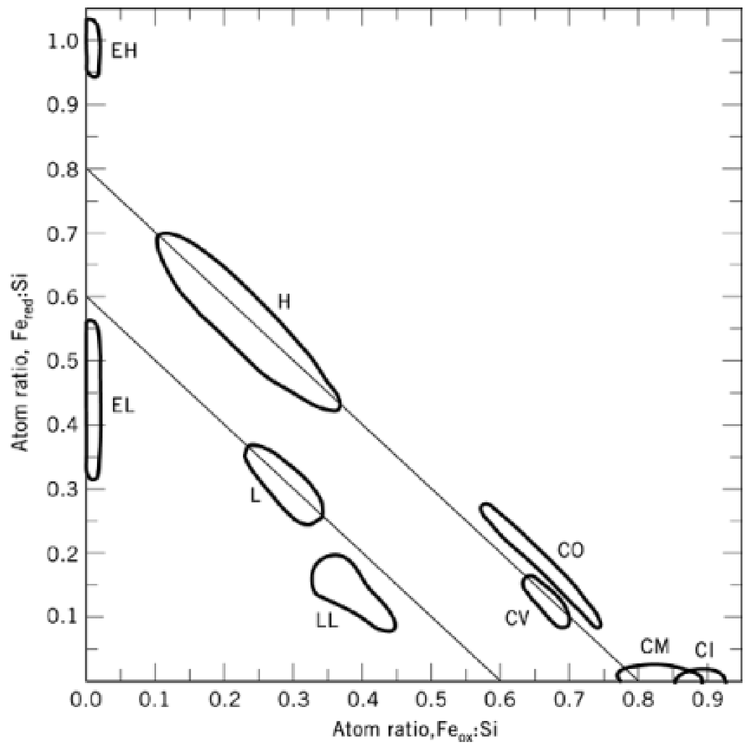

Fig. 2. The plot of total reduced iron, Fe_{red}, and oxidized iron, Fe_{ox}, normalized to Si abundance shows how the chondrite classes fall into groups distinguished by oxidation state and total Fe:Si ratio. The solid diagonal lines delineate compositions having constant total Fe:Si ratios of 0.6 and 0.8. The fractionation of total Fe:Si is likely the result of the relative efficiencies of accumulation of metal and silicate materials into the meteorite parent bodies. The variation in oxidation state is the result of conditions in the solar nebula when the solids last reacted with gas. Terms are defined in Table 1 (3).

abundant in the CV chondrites and are responsible for the unusually high refractory element abundances in this class (Fig. 3).

Most meteorite classes can also be distinguished by the oxygen isotope compositions (12). This remarkable distinction illustrated in the three-isotope plot shown in Figure 4, correlates with compositional and mineralogical classification. Before the solar system formed, oxygen existed in the precursor materials in both solid and gaseous species each potentially having its own oxygen isotopic composition traceable to variable inputs from materials of different nucleosynthetic sources. Oxygen arising from at least three isotopically distinct reservoirs, plus mass-dependent fractionation in the solar system, resulted in clear separation of the isotopic compositions. All natural terrestrial materials lie on the terrestrial fractionation line and a truly unique property of extraterrestrial samples is that, with the exception of the lunar samples, the extraterrestrials do not fall on this line. The highest deviations from terrestrial values are found in the CAIs where materials have been found that have as much as 5% excess ^{16}O.

Within each chondrite class there are petrographic grades that relate to alteration processes that occurred within the meteorite parent body. The grades range from 1 to 6 (13), although no class has examples in more than four grades. Grades 3 to 6 represent the effects of thermal metamorphism where the higher number is the more strongly altered. Grades 1 and 2 occur only for the CI and CM chondrites, respectively. CI and CM chondrites have been extensively altered by aqueous alteration in their parent bodies probably as a result of the melting of ice followed by reactions of preexisting phases. The sulfates, magnetite, carbonates, and hydrated

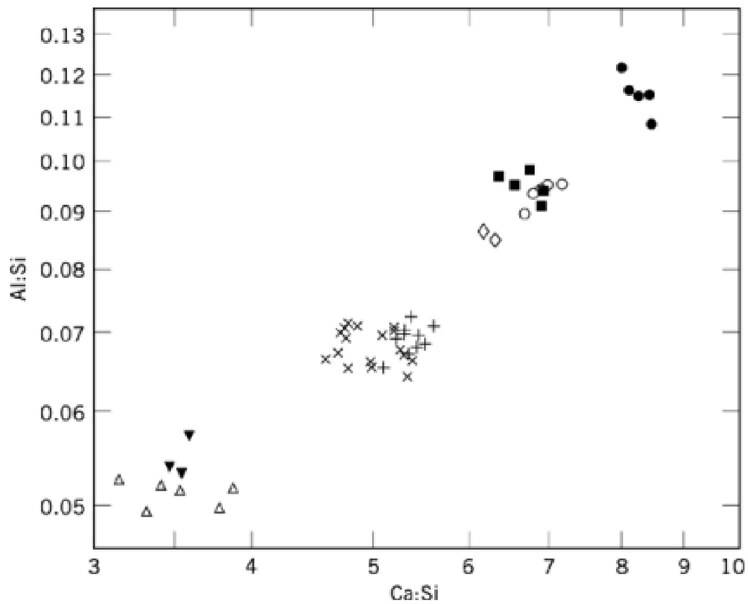

Fig. 3. The bulk Al:Si and Ca:Si ratios of chondrites fall into discrete groups where • represent CV; ■, CM; ○, CO; ◇, CI; +, H; ×, L; ▼, EL; and △, EH. The fractionation of these refractory elements is believed to be the result of relative efficiencies of incorporation of condensed solids rich in early high temperature phases into the meteorite parent bodies at different times and locations in the solar nebula. The data are taken from Reference 3.

silicates in CI chondrites are largely secondary minerals resulting from aqueous processes that apparently occurred at near freezing temperatures. Veins of water-soluble sulfates deposited from solution exist in CI and some CM chondrites. Primitive ^{87}Sr:^{86}Sr ratios imply that vein formation occurred more than 4.4 Gyr ago (14).

The ordinary chondrites show a range of thermal alteration that is evidence of parent-body heating to temperatures above 800°C for the petrographic grade 6 chondrites. These effects show up in many ways. The least-heated ordinary chondrites are petrographic grade 3 meteorites, also known as the unequilibrated ordinary chondrites (UOC). These are characterized by the high degree of disequilibrium among different phases. For example, the Fe:Mg ratios of olivine are highly variable in H3 chondrites, whereas all olivines in the heated H6 have the same Fe:Mg ratio because they were equilibrated owing to thermal diffusion at elevated temperature. There are many effects that occur in the metamorphic sequence ranging from 3 to 6. Glass, which is common in grade 3, is completely devitrified above grade 5; Ni, which exists in sulfides at several percent in lower grades, is less than 0.5% in grades above 4 because it has diffused into metal; and secondary feldspar is absent in low petrographic grades but occurs as clear interstitial grains in grade 6. Metamorphic heating causes extensive alteration of the initial phases. A primitive grade 3 chondrite is composed of well-defined chondrules surrounded by dark, fine-grained matrix; the metamorphosed chondrites have poorly defined chondrules, and the matrix is composed of coarse grains that have grown at the expense of the original fine-grained matrix. For grades 3 to 6 a precise determination of petrographic grade can be determined by measurement of thermoluminescence, a property indicative of the amount of feldspar produced from glass as a result of thermal metamorphism (15).

1.1.2. Achondrites

The achondrites are differentiated stony meteorites that are apparently derived from parent bodies that were heated to at least partial melting temperatures. Achondrites do not contain chondrules and do not have

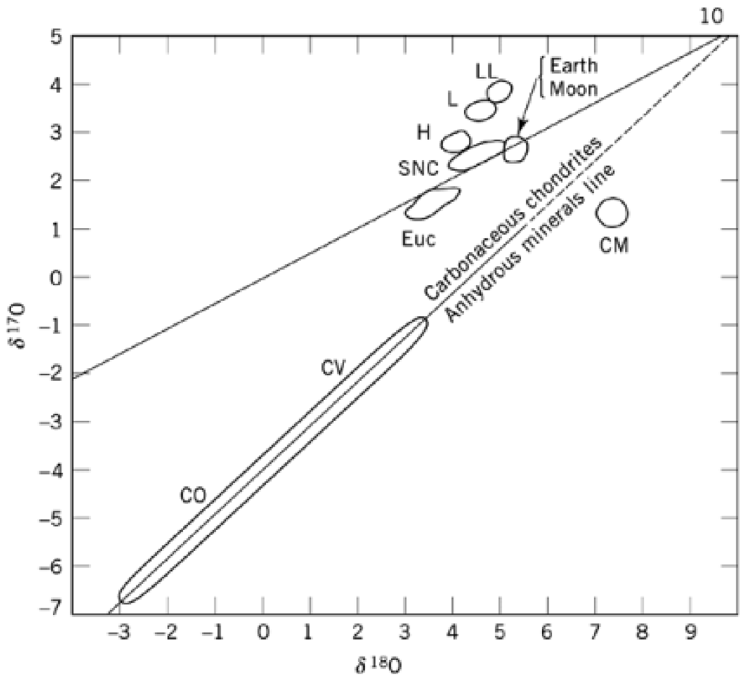

Fig. 4. The bulk oxygen isotopic composition of different meteorite classes where (—) is the terrestial fractionation line. The δ notation refers to the normalized difference between ^{17}O:^{16}O or ^{18}O:^{16}O ratios to those in standard mean ocean water (SMOW) in relative units of parts per thousand. The meteorites formed from materials that were enriched or depleted in ^{16}O and their bulk compositions plot off of the terrestrial line which has a slope of 1/2 owing to mass dependent fractionation. Some of the anhydrous minerals from carbonaceous chondrites fall on a line having a slope of 1. These anomalous compositions may be produced by mixing with an ^{16}O-rich component that has a different nucleosynthetic history than mean solar system material. The data are taken from Reference 10.

elemental compositions that match solar abundances for condensable elements. These materials are old but their properties were more determined by planetary processes such as melting and differentiation than by primary nebular processes, such as condensation and accretion. Many of the achondrite subclasses can be combined into three basic groups: HED, SNC, and lunar groups. The HED group comprises the howardite, eucrite, and diogenite subclasses, which together are responsible for more than 6% of all meteorite falls. Eucrites are basalts that formed by rapid cooling of a basaltic composition magma and are largely composed of plagioclase and pryoxene. The diogenites are coarser grained, dominated by orthopyroxene, and have a mantle-like composition from which the eucrite basalts could have been derived. The howardites are breccias composed of mechanically mixed fragments of eucrite and diogenite components. The mineralogical composition and identical oxygen isotopic compositions of the HED meteorite clan is consistent with possible derivation from a single differentiated parent body. The spectral reflectivity of the HED meteorites is a strong and essentially unique match with the 500-km asteroid Vesta and its family of fragments. This suggests that this single asteroid is the source of the HED meteorite group (16).

The SNC achondrites are composed of the Shergotty, Nakhla, and Chassigny subgroups. Although the different specimens in this group have separate lithologies, they are all highly differentiated igneous rocks having properties consistent with derivation from a geochemically evolved body of planetary size. Their crystallization ages of only a Gyr clearly set them apart from nearly all other meteorites. Because it can be shown that SNC achondrites are not lunar material and are unlike the largest known asteroids, by default the most likely parent body of adequate size is Mars (17). Geochemical evidence and the similarity of trapped gas to actual atmospheric measurements on Mars have provided strong evidence that the SNC meteorites are samples of Mars. The only known ejection mechanism capable of launching rocks from a planetary surface at speeds in excess of the escape velocity involves significant impacts of asteroids and comets. At one time it was thought that this mechanism was implausible because the shock energy would melt or vaporize any fragments, but the discovery of impact ejected lunar meteorites on the Earth has demonstrated that this is a viable mechanism.

Among the rarest of all meteorites are the lunar meteorites. Isotopic, mineralogical, and compositional properties of these samples provide positive identification as lunar samples because of the unique properties of lunar materials that have been discovered by extensive analyses of lunar materials returned by the manned Apollo and unstaffed Luna missions. All but one of the lunar meteorites that have been found to date have been recovered from Antarctica.

1.1.3. Irons

Approximately 4% of meteorite falls are irons. Because they are distinctive rocks and weather relatively slowly, most meteorites that were not seen to fall, but were found accidentally, are irons. Iron meteorites represent metallic iron and siderophile elements that fractionated from molten parent bodies. They may have been cores of asteroids or they may have only been localized metal accumulations. The measured cooling rates of these objects at the time of formation imply that they are derived from bodies smaller than planets. Irons are predominantly composed of metallic iron having nickel, Ni, contents ranging from 6% to as much as 18%. The dominant minerals are kamacite and taenite, although other phases such as troilite [1317-96-0], graphite, schreibersite [12424-46-3], diamond, and even silicates occur as inclusions. Many of the irons have a distinctive crystal structure called the Widmanstatten pattern (Fig. 5), produced by slow cooling. Iron meteorites fall into more than a dozen subgroups distinguished by trace-element composition. These groups are most clearly isolated on the basis of the gallium, germanium, and iridium abundances normalized to nickel.

1.1.4. Stony Irons

The stony iron meteorites are composed of substantial iron and silicate components. The pallasites contain cm-sized olivine crystals embedded in a solid FeNi metal matrix and have properties consistent with formation at the core mantle boundary of differentiated asteroids. The mesosiderites are composed of metal and silicates that were fractured and remixed, presumably in the near-surface regions of their parent bodies.

1.2. Origin

Typical meteorites have formation ages of 4.55 Gyr and exposure ages of only 10^7 years, during which time they existed as meter-sized bodies unshielded to the effects of cosmic rays. With the exception of the SNC (Martian) and lunar meteorites it is widely believed that most conventional meteorites are asteroid fragments liberated relatively recently by collisions and transferred to the Earth by gravitational perturbations. The principal source location is thought to be the zone 2.5 AU (one AU is equal to the mean distance between the Earth and the Sun) from the Sun where the orbital frequency about the Sun is exactly three times that of Jupiter. Objects in this zone undergo chaotic perturbations that change relative circular orbits to Earth-crossing orbits on a 10^6-yr time scale. The three meteorites for which accurate entry paths into the atmosphere have been determined can be traced to asteroidal origins.

The general scenario for the history of meteorites is that they are fragments of asteroids that have been stored in the asteroid belt 2.2 to 3.3 AU from the Sun. Early in the history of the solar system many if not all of the asteroids were heated to temperatures ranging from 0°C to as high as 1300°C. The source of this heating may have been resistive heating from electrical currents by magnetic fields in the solar nebula or the decay of ^{26}Al and ^{60}Fe, short-lived radionuclides that have been shown to have been present inside meteorites at the time of their formation. Many of the chondrite parent bodies were not heated severely and still retain

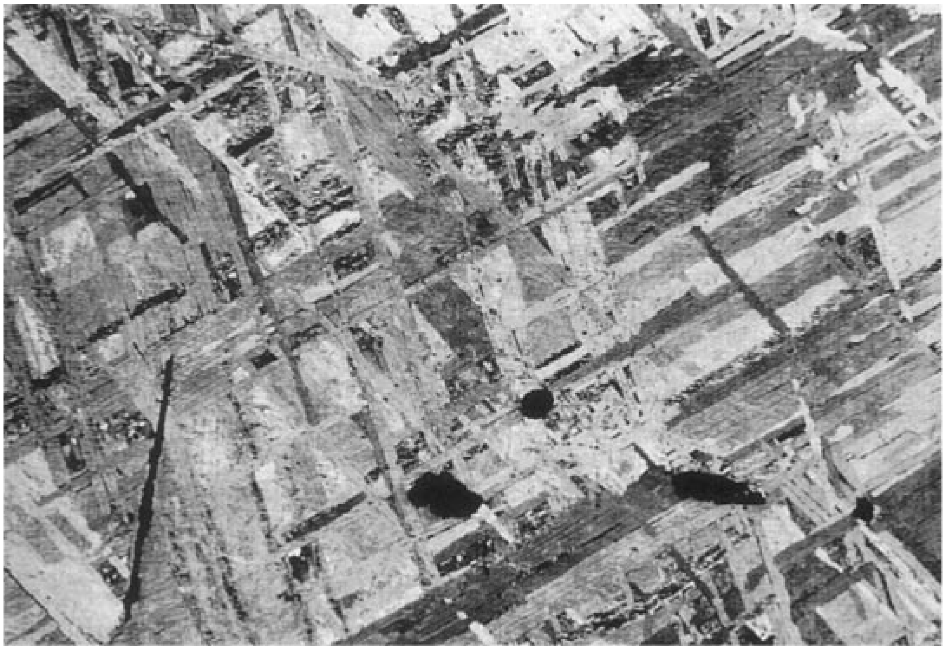

Fig. 5. The Widmanstatten pattern in this polished and etched section of the Gibbeon iron meteorite is composed of intergrown crystals of kamacite and taenite, NiFe phases that differ in crystal structure and Ni content. Ni concentration gradients at crystal boundaries in this 3-cm-wide sample can be used to estimate the initial cooling rates and corresponding size of the asteroid from which the meteorite was derived.

many of the properties of the nebular materials from which they formed. These properties include chondrules formed in the nebula by yet unknown processes, reworked nebular materials, primary nebular condensates, and interstellar grains that actually predate the solar system. One of the most remarkable aspects of chondrites is that they contain preserved interstellar grains retaining isotopic and mineralogical properties that have survived since they formed in circumstellar regions around other stars. These phases include diamonds; silicon carbide [409-21-2], SiC; titanium nitride [25583-20-4], TiN; and graphite (18).

2. Interplanetary Dust

Interplanetary dust particles (IDPs) are the submillimeter-size regime of the solar system meteoroid inventory ranging in size from tens of nanometers to 1000 km in diameter. These particles are short lived in the interplanetary medium because of the effects of self-collisions and orbital decay caused by the drag component of sunlight (the Poynting-Robertson effect). Most of the IDPs that now reach the Earth were liberated from comets and asteroids within the last 10^6 years. Over 40,000 tons of IDPs impinge on the Earth annually and cumulatively they are the dominant meteoritic mass input on time scales shorter than 10^7 years. Interplanetary dust in the size range of a few micrometers to a millimeter can be collected in and below the atmosphere, and recovered particles provide an important sampling of asteroids and comets. These samples complement conventional meteorites because they include specimens of objects that for a variety of reasons do not either reach the Earth or survive atmospheric entry in greater than cm-sized pieces to become conventional meteorites (19). Dust provides a broader and less biased sampling of interplanetary materials because small samples of

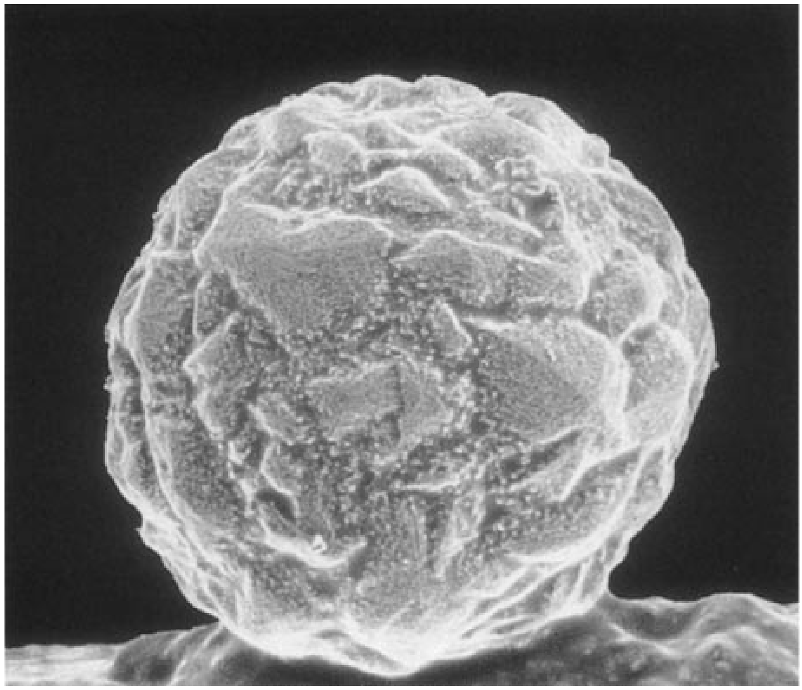

Fig. 6. A 0.3-mm-diameter cosmic spherule collected from the ocean floor. The particle is composed of olivine, glass, and magnetite and has a primary element composition similar to chondritic meteorites for nonvolatile elements. The shape is the result of melting and rapid recrystallization during atmospheric entry.

fragile materials can survive atmospheric entry without crushing. Additionally, sunlight pressure effects cause all dust beyond the Earth's orbit to evolve toward the Sun where collisions with Earth are possible.

Small meteoroids are not subjected to high ram pressures during entry because they decelerate at altitudes near 90 km, where the air density and corresponding ram pressure from collisions with air molecules is small. Conventional meteorites are larger and penetrate deeper into the atmosphere with high velocity, where they are subjected to crushing ram pressure. Unlike conventional meteorites which reach the Earth only by rare gravitational perturbation, dust from all bodies beyond the Earth's orbit, if not immediately ejected from the solar system by radiation pressure, experiences the effects of radiation drag causing it to inexorably spiral toward the Sun and past the Earth's orbit.

2.1. Collection

IDPs can be collected in space although the high relative velocity makes nondestructive capture difficult. Below 80 km altitude, IDPs have decelerated from cosmic velocity and collection is not a problem; however, particles that are large or enter a very high velocity are modified by heating. Typical 5-μm IDPs are heated to 400°C during atmospheric entry whereas most particles larger than 100 μm are heated above 1300°C, when they melt to form cosmic spherules (Fig. 6).

The flux of 10-μm particles is $1/(m^2{\cdot}d)$, a value high enough that these IDPs can be collected directly using high altitude aircraft (20). The spatial density of 10-μm IDPs at 20-km altitude is $10^{-3}/m^3$. Particles >100 μm fall at a rate of only $1/(m^2{\cdot}yr)$ and can only effectively be collected after they have fallen to the ground and concentrated in a surface deposit. The small particles are collected primarily using stratospheric aircraft

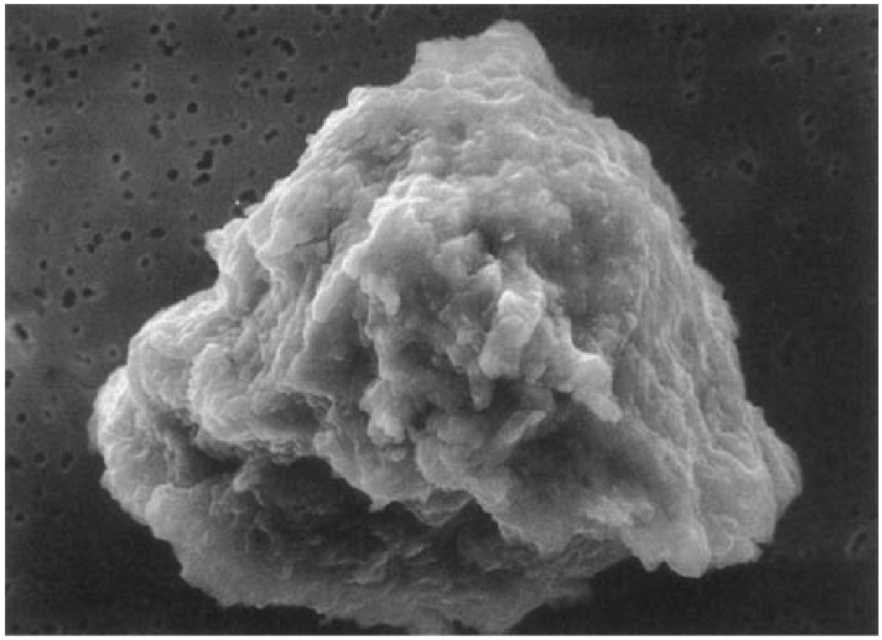

Fig. 7. A 10-μm interplanetary dust particle that is not porous and contains hydrated silicates. The particle's elemental composition is a good match to solar composition except for very volatile elements like the noble gases.

although they have also been recovered by melting pristine Antarctic ice. The larger IDPs have been collected from deep sediments, Greenland ice, and Antarctic ice, and a few other selected terrestrial environments that allow the extraterrestrial to be efficiently isolated and distinguished from terrestrial particles. Many of the $>100-\mu$m cosmic particles are spherules and their shape assists in making a distinction from other materials.

Extraterrestrial dust particles can be proven to be nonterrestrial by a variety of methods, depending on the particle size. Unmelted particles have high helium, He, contents resulting from solar wind implantation. In 10-μm particles the concentration approaches $1/(cm^3{\cdot}g)$ at STP and the ^3He:^4He ratio is close to the solar value. Unmelted particles also often contain preserved tracks of solar cosmic rays that are seen in the electron microscope as randomly oriented linear dislocations in crystals. For larger particles other cosmic ray irradiation products such as ^{53}Mn, ^{26}Al, and ^{10}Be can be detected. Most IDPs can be confidently distinguished from terrestrial materials by composition. Typical particles have elemental compositions that match solar abundances for most elements. Typically these have chondritic compositions, and in descending order of abundance are composed of O, Mg, Si, Fe, C, S, Al, Ca, Ni, Na, Cr, Mn, and Ti.

The most common IDPs are black objects having approximately solar elemental composition except for very volatile elements such as the noble gases. There are particles that deviate strongly from this pattern but they are rare and are usually dominated by a single mineral such as FeS, olivine, or FeNi metal. Most of the particles can be grouped into two classes: one contains hydrated minerals such as serpentine [12168-92-2] and smectite [12199-37-0]; the other, ones that are anhydrous. The hydrated particles are often nonporous (Fig. 7) and have some mineralogical properties similar to the CM and CI chondrites. Many of the anhydrous IDPs are porous materials having an aggregate structure (Fig. 8). The anhydrous particles are glass- and carbon-rich materials that contain FeNi, FeS, olivine, and pyroxene but have no close analogue among conventional meteorites.

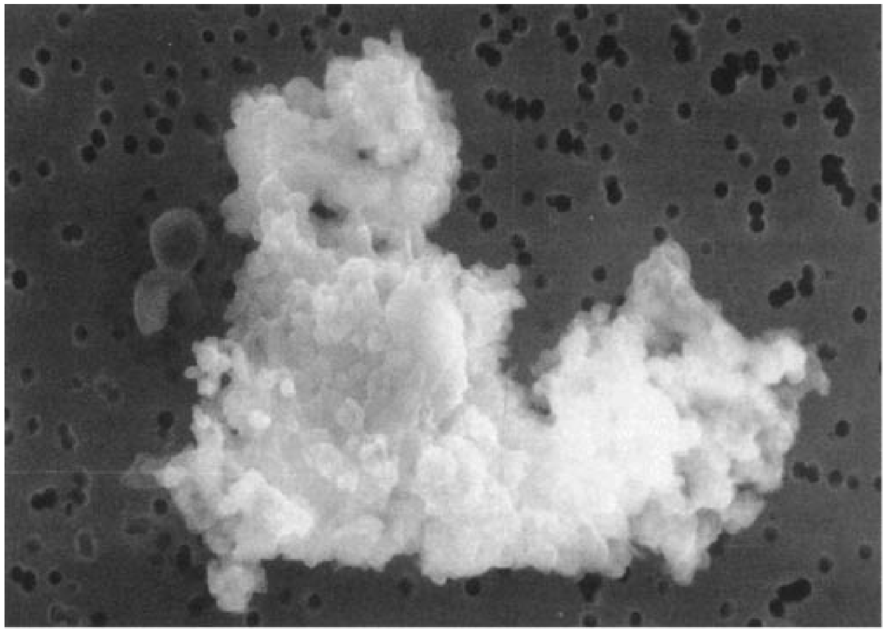

Fig. 8. A porous interplanetary dust particle collected in the stratosphere. The particle is 10 μm across and is composed of anhydrous minerals.

2.2. Origin

Individual IDPs are short-lived and the long-term presence of dust in the solar system implies that there must be sources capable of generating the approximately 10^7 kg/s of new dust required to balance losses by collisions, ejection by radiation pressure, and spiraling into the Sun owing to the Poynting-Robertson effect. For sizes $>10\ \mu$m, it has long been known that comets and asteroids are the principal source. Particles are liberated from asteroids by collisions of both asteroids and asteroid debris. Whereas collision velocities are high, most of the liberated dust is not strongly modified by the collision process and is ejected with a space velocity close to that of the more massive of the two colliding bodies. Dust in the asteroid belt has been detected by its thermal emission in the infrared at wavelengths $>10\ \mu$m. The orbiting IRAS infrared telescope discovered dust bands in the asteroid belt that correlate with the principal collisionally-produced asteroid families (21) (see Infrared technology). Dust generated in the asteroid belt undergoes orbital decay owing to light pressure drag and spirals toward the Sun reaching the Earth on relatively low velocity orbits. Dust from comets is released when solar heating sublimes the ice matrix in comets. Dust is ejected, and because of the effects of light-pressure drag and ejection velocity, it forms the dust tail than can extend to lengths of over 10^8 km. Most of the comet dust that is collectable on Earth is believed to have been derived from the Kuiper belt comets that reside in a flattened distribution extending from the region of the outer planets to distances of a few 100 AU from the Sun. At the time of dust release these bodies have evolved to short-period comets whose orbits pass close to the Sun. Dust from these comets reaches the Earth on relatively high velocity eccentric orbits. The dust from both comets and asteroids is believed to be samples of early solar system materials that has been relatively well preserved over the age of the solar system inside moderately small bodies.

Methods used to determine the temperature and hence entry velocity of 10-μm particles entering the atmosphere have provided direct information of the relative abundances of asteroid and comet dust reaching the Earth. Helium content, volatile content, and mineralogical indicators can be used to determine the maximum temperature reached during atmospheric entry. Comet dust enters faster than asteroid dust and accordingly is more strongly heated. These studies indicate that $\sim$20% of the 10-μm IDPs in the Earth's atmosphere are of cometary origin and that >50% are derived from asteroids. Taking into account the gravitational focusing enhancement at Earth, the abundance of comet dust in space is thought to be higher than 20%.

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