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Chondrites

The chondrites are the most common type of METEORITE falling to Earth from space. They acquire their name because most of them contain 'chondrules' (from the Greek, 'chondros', a grain) which are silicate beads sometimes found in large numbers. The chondrules have always fascinated scientists. The inventor of the petrographic microscope, H C Sorby, described them as droplets of fiery rain. They are essentially glassy beads made by a violent but brief heating event that caused dust grains to form millimeter-sized melt droplets. However, the cause of the heating remains a mystery. The most important feature of the chondrites is that, with the exception of a few highly volatile elements, they have the same composition as the Sun. They are also extremely ancient rocks, having formation ages comparable with the age of the solar system (4600 million years). Finally, they have unique textures suggestive of accumulation of

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diverse components with little or no subsequent alteration. In contrast, the ACHONDRITES are meteorites that have distinctly non-solar composition and are igneous rocks that formed by various types of volcanism.

The largest chondrite seen to fall from space is the 4000 kg Jilin, while the largest whose fall was not observed but for which the meteorite found on the surface of the Earth is the Tsarev chondrite that was found in Russia in 1968. The most famous chondrite is probably the ALLENDE METEORITE, which fell in Mexico in 1969. About 2 t were recovered strewn across farmland in Chihuahua province. The Allende chondrite is famous for the large number of white silicate aggregates with extraordinary chemical and isotopic properties. The 691 g Semarkona chondrite, which fell in India in 1940, is scientifically well known because it is the member of the largest chondrite class that most closely resembles original solar system matter.

Meteorites usually produce spectacular effects as they fall through the atmosphere, fireballs, many sonic booms and even smells are produced, and the surfaces of the surviving stones are blackened where a thin skin of material melted during atmospheric passage. The meteorites usually break into many pieces that are strewn over an ellipse on the Earth with the heaviest pieces travelling furthest. The Pultusk meteorite produced 100 000 fragments. About 850 chondrites have been seen to fall and placed in the world's museums, and nearly 20 000 fragments have been found on the Earth, mainly in North America, north Africa, central and western Australia and, especially, Antarctica.

This article describes the classification and basic properties of chondrites, their physical history as determined from isotopic studies, radiometric dating and petrology, and some current ideas for their origin.

Classification and basic properties of chondrites

The chondrite classes are indicated in table 1, along with information on their major properties. Also included are two classes of 'primitive achondrites'. These have traditionally been regarded as achondrites because of their igneous textures, but their composition is solar and it is now assumed that they are chondrites that melted without changing composition.

Although chondrites have the same proportions of most elements as the Sun, two volatile elements that are not present in solar proportions are sulfur and oxygen. The abundance of these elements, oxygen in particular, varies significantly among the chondrites. This has important implications for the minerals present. In the EL and EH chondrites (collectively termed 'enstatite chondrites'), iron is in the metal and sulfide form, but little or none is in the silicate form. The dominant silicate mineral is enstatite, $MgSiO_3$, after which the class is named. The H, L and LL chondrites (collectively termed 'ordinary chondrites') contain more oxygen than the enstatite chondrites. Thus while some of the iron exists as metal and sulfide, much is in the silicate form as the stony (silicate) minerals olivine and pyroxene. (Olivine is a solid state solution of Mg_2SiO_4 and Fe_2SiO_4, the Fa term in table 1 referring to the percentage of Fe_2SiO_4 present, while pyroxene is a solid solution of $MgSiO_3$ and $FeSiO_3$, the Fs term in table 1 referring to the percentage of $FeSiO_3$ present.) The CI, CM, CV and CO chondrites (collectively termed 'carbonaceous chondrites') contain more oxygen than the other chondrites and in some the iron no longer exists in the metal form but is entirely replaced with magnetite and similar minerals. The CARBONACEOUS CHONDRITES also contain higher amounts of volatile constituents than the other chondrites, the CI chondrites being 20% water and therefore best considered as rather hard balls of mud.

These properties can conveniently be displayed by a plot of iron in the metal form against iron in the sulfide and silicate form (figure 1(*a*)). On such a plot, first used by Nobel laureate Harold Urey and his colleague Harmon Craig, the chondrites will lie on a diagonal with oxygen-poor meteorites on the top left and oxygen-rich meteorites on the bottom. The diagonal will be the 'solar total iron' line if the ratio of iron to silicon is equal to the solar value. However, the chondrites move away from the solar diagonal, indicating that, in addition to the differences in the amount of oxygen they contain, some chondrites contain different amounts of total iron.

Other properties seem to vary with these chondrite classes, such as the abundance of highly refractory (non-volatile) elements that show small but significant decreases from solar as we go from carbonaceous to ordinary to enstatite chondrites. Similarly, the relative abundance of the three isotopes of oxygen in the different chondrite classes is highly characteristic. Carbonaceous chondrites (CI chondrites excepted) contain a greater proportion of the major oxygen isotope (^{16}O) than rocks from the Earth and Moon, whereas enstatite chondrites and CI chondrites have similar proportions to the Earth and Moon and ordinary chondrites have a lower proportion of ^{16}O. The biggest effects in oxygen isotopes are displayed by the CV chondrites and appear to be related to the white silicate aggregates that are characteristic of this class.

The main questions posed by the chondrite classes is that, given that chondrites are ancient and that they are essentially solar in composition, how did these variations in iron chemistry, amount of iron and the other properties come about? What do they tell us about conditions in the early solar system?

One clue to the nature of the process that gives rise to these properties is the nature and abundance of the chondrules and the relative sizes of the chondrules and metal grains (figure 1(*b*)). The abundance of chondrules falls from about 75 vol% in the ordinary chondrites to 35 vol% in enstatite and CV and CO chondrites to less than 10 vol% in CM and essentially zero in CI chondrites. Chondrules are highly diverse, some containing iron-rich silicates and being relatively rich in volatile elements and some containing iron-poor silicates are being depleted in volatile elements. Thus it is at least arguable that some of the oxygen and refractory element trends in figure 1(*a*)

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Table 1. Classes of chondrites and some of their properties.

	Statistics		Texture				Composition				
Class	Falls (number)	Finds (number)[a]	Chondrule (vol%)	Chondrite (μg)	Metal (vol%)	Metal (μg)	Fe/Si (a/r)	Mg/Si (a/r)	Fa,Fs (mol%)	δ^{17}O[b] (‰)	δ^{18}O[b] (‰)
Carbonaceous chondrite											
CI	5	0 (2)	0	–	0	–	0.86	1.05	nd,nd	9.23	16.84
CM	13	4 (156)	5–15	270	≤0.1	–	0.80	1.05	15,2	3.0	10.9
CO	5	37 (81)	40	150	3.6	nd	0.77	1.05	14.3,4.0	−3.0	−2.6
CV	6	11 (81)	40	1000	2.3	nd	0.78	1.03	8.4,4.0	−15.4	−11.3
CK	1	7 (73)	15	700	0	–	0.78	1.09	30.9,26.9	−1.8	−5.8
CR	3	12 (76)	55	700	10.7	nd	0.82	1.05	4.7,3.4	2.29	6.25
Ordinary chondrites											
H	311	974 (6881)	70	380	8.4	190	0.81	0.96	19.3,16.8	2.9	4.1
L	425	855 (6332)	70	620	4.1	160	0.57	0.93	25.2,20.9	3.5	4.6
LL	73	114 (960)	70	750	2.0	140	0.52	0.94	31.3,25.2	3.9	4.9
R	1	4 (10)	12–40	380	<0.1	–	0.60	0.94	38,0–32	5.52	5.07
Enstatite chondrites											
EH	8	4 (63)	20	280	10.1	41	0.95	0.68	0.4,0.3	3.0	5.6
EL	7	8 (30)	20	480	10.2	78	0.62	0.81	0.4,0.3	2.7	5.3
Primitive achondrites											
Bra[c]	0	4 (6)	–	–	nd	nd	0.65	1.16	33,18	1.61	3.48
Aco[d]	1	2 (12)	–	–	2	nd	0.70	1.06	11.9,12.6	3.73	1.00

[a] Non-Antarctic finds, with all finds in parentheses.

[b] The δ symbol refers to the difference in parts per thousand of the $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios between the sample and a standard sample of ocean water.

[c] Brachinites.

[d] Acopulcoites.

(a/r) = atomic ratio

reflect the abundance and proportion of the different types of chondrules. Metal grain size also varies considerably from class to class. Enstatite chondrites have the smallest and ordinary chondrites the largest metal grains, while carbonaceous chondrites generally have little or no metal.

History of chondrites

If one looks at a series from the same class under the microscope there is often a wide range of textures, with the chondrules being distinct in some chondrites and blurred in others. The chondrules are essentially grains of olivine and pyroxene surrounded by a material that is glassy in some chondrules, translucent in others and crystalline in yet others. Similarly, the matrix between the chondrules and metal grains is fine grained in some chondrites and coarse grained in others. In addition to these physical trends, the composition of mineral grains and phases becomes more uniform as textures become blurred. These effects are all attributed to heating of the rock after its assembly. The effect is known as metamorphism, and it is described by a numbering system from 3 to 6 with unmetamorphosed type 3 and heavily metamorphosed meteorites being type 6. From detailed studies of the chemistry of phases in chemical equilibrium we can estimate that types 3, 4, 5 and 6 correspond approximately to temperatures of 400–600 °C, 600–700 °C, 700–750 °C and 750–950 °C, respectively. Types 1 and 2 refer to chondrites metamorphosed in the presence of considerable amounts of water (~50 vol%), the type 1 at 100–150 °C and type 2 at <20 °C. From compositional profiles in the metal of ordinary chondrites, caused by incomplete equilibration, we can estimate that cooling rates following metamorphism were typically 10–100 K Myr^{-1}.

Another process that most if not all the chondrites have suffered is reflected in the naked-eye appearance of the chondrites. They often appear to be made up of fragments of previously existing rocks. The Fayetteville meteorite (figure 2(*a*)) is an excellent example of this texture. Technically, the process is referred to as 'brecciation' and the rocks are referred to as 'BRECCIAS'. Fragments of perfectly normal chondrite are sometimes surrounded by a darker 'soil' made of crushed chondrites and being rich in inert gases, carbon and crystals that have been damaged by radiation. These meteorites are referred to as 'gas-rich regolith breccias'. They were the surface debris of some airless body exposed to solar wind and energetic solar radiations. The Apollo astronauts found similar rocks on the Moon.

In addition to metamorphsim and brecciation, many meteorites show evidence for sudden excursions to high temperatures followed by very rapid cooling. Crystals are cracked and deformed, and metal and sulfide minerals are melted and forced down cracks, and sometimes minerals acquire unusual textures. These effects can be reproduced in the laboratory by exposing the chondrites to shock waves produced by plastic explosives or large guns. The effects are classified as a series of levels, S1, S2, S3, S4, S5 and S6, that refer to shock pressures of <5 GPa, 5–10 GPa, 10–20 GPa, 20–30 GPa, 30–50 GPa and >50 GPa,

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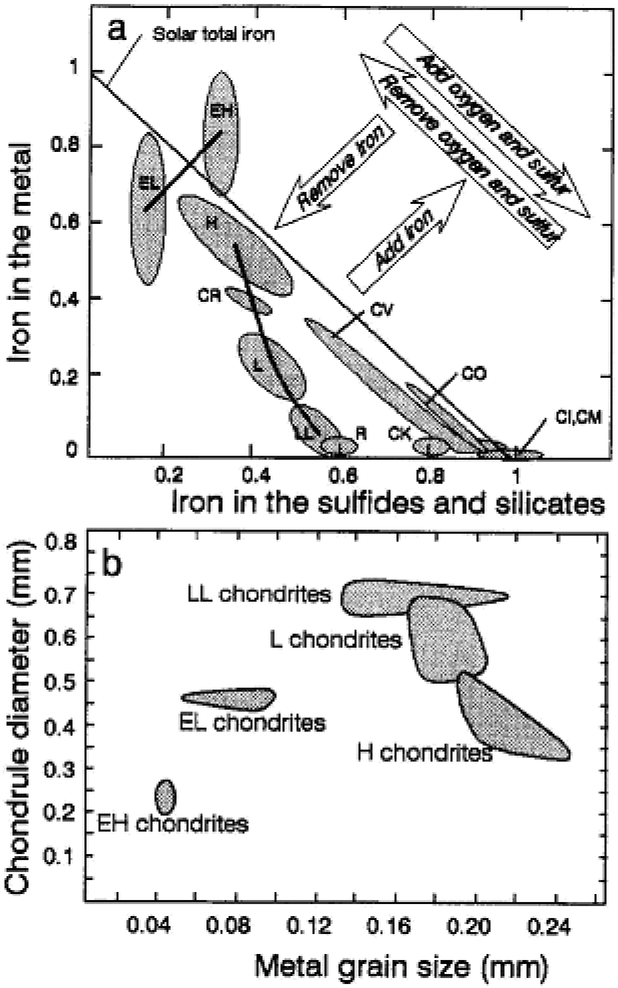
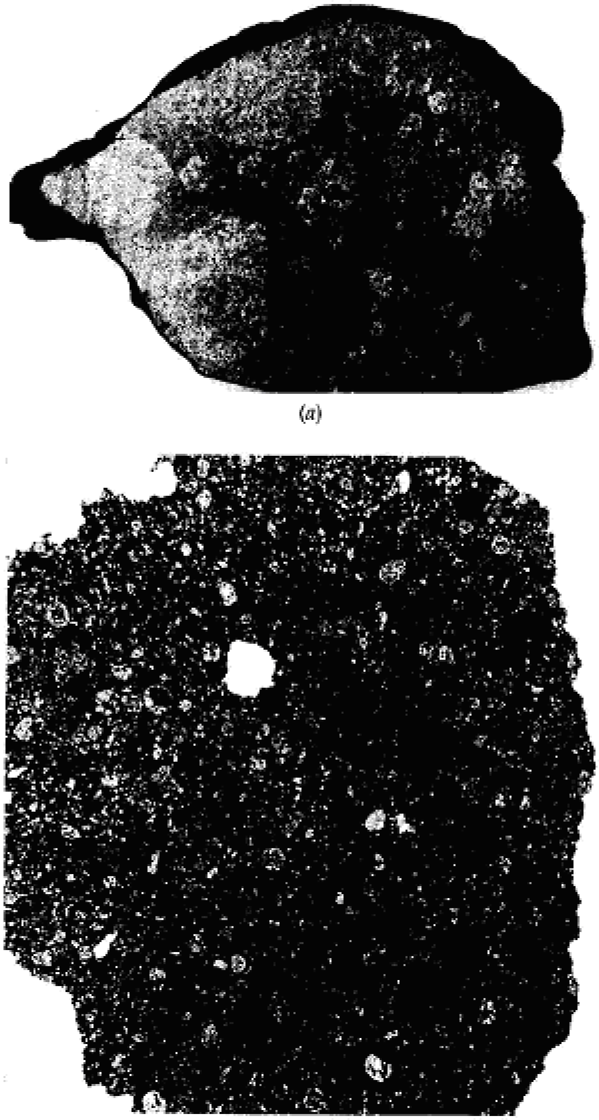


Figure 1. The basic properties of chondrites are summarized in these two plots. (*a*) Iron exists in three forms, as metal, sulfide and silicates. Plotting iron in the metal form (as ratio of iron atoms to silicon atoms) against iron the sulfides and metal produces several different fields, each representing a different chondrite class. How the classes relate in terms of adding or removing iron, sulfur and oxygen are indicated by the large arrows. (*b*) Physically, the chondrite classes are characterized by the size of their chondrules and metal grains. The carbonaceous chondrite classes are not shown because they contain little or no metal, but they do contain very large amounts of fine-grained silicate matrix.


(*a*)

(*b*)

Figure 2. (*a*) A cut face of the chondrite that fell at Fayetteville, Arkansas, on 26 December 1934. The black fusion crust produced during atmospheric passage can be seen around the edge. The interior consists of light fragments of normal H chondrite embedded in a darker 'matrix' of crushed H chondrite material mixture that is physically similar to the 'soil' on the Moon. Fayetteville is a chondrite that is described as a gas-rich regolith breccia fron the surface of an airless body. The cut face is 9 cm in its longest dimension. (Johnson Space Center photograph S84-32404.) (*b*) A slice from the Indarch EH3 chondrite cut so thin that light can pass through and reveal its internal texture. The sulfide and metal grains are opaque and appear black, while the many chondrules appear as light gray circular objects typically 0.5 mm in diameter. The longest dimension of the thin section is 1.4 cm. (Smithsonian Institution photograph M-1249.)

respectively (1 Gpa, or gigapascal, is equal to about 10 000 atm). The source of the shock wave experienced by the chondrites is almost certainly impact between two ASTEROIDS in space.

Some of the best information we have on the history of chondrites is provided by various dating methods (figure 3). As soon as the meteorite is removed from its original parent body, and acquires meter-sized dimensions, COSMIC RAYS bombard the stone and create isotopes not otherwise present. From these isotopes it is possible to calculate the duration of exposure to cosmic rays. It is frequently found that large numbers of chondrites of a given class were exposed at the same time,

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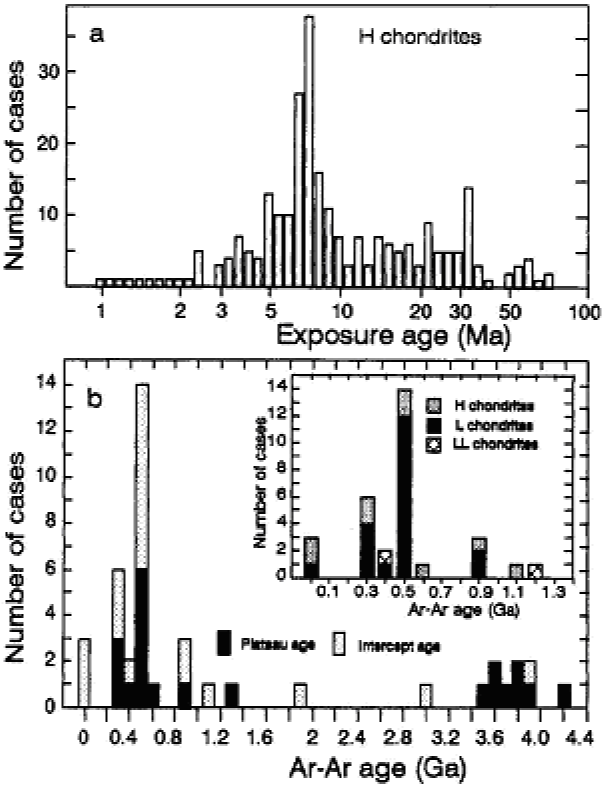

Figure 3. Two kinds of ages provide important insights into the history of the chondrite meteorites. (*a*) The duration of exposure to cosmic rays, calculated from the abundance of isotopes produced by cosmic ray bombardment of the meteorite. The peak in the histogram at 8 million years indicates that many or most of the individual meteorites falling to Earth were exposed to cosmic rays at the same moment and must have been part of the same single object prior to that break-up event. The data shown are for the H chondrites but other classes often show similar tendencies towards preferred cosmic ray exposure ages. (*b*) The Ar–Ar age essentially measures the time during which the ^{40}Ar accumulated in the meteorite as a result of radioactive decay of ^{40}K. The peak in the histogram at 500 million years shown mainly by the L chondrites indicates that at this time a large number of L chondrites had the Ar–Ar 'clock' reset to zero by loss of previously accumulated ^{40}Ar. Thus, most members of this class also experienced a common heating event at one time, indicating that they too were part of the same object at the time of that event. 'Plateau' and 'intercept' ages refer to different ways to handle the data.

and this is strong evidence that all or most of the chondrites were released from the same parent object at that time. The best example is the H chondrite class, most of whose members became exposed to cosmic rays 8 million years ago. Several other chondrite classes display similar peaks in their exposure age distributions.

A different dating method leads to the same conclusion for the other major chondrite class, the L chondrites. The 'Ar–Ar age' is based on the radioactive decay of ^{40}K to ^{40}Ar; the potassium is measured in the laboratory from the abundance of another experimentally produced isotope, ^{38}Ar. Most of the L chondrites have Ar–Ar ages of about 500 million years, and many of these are intensely shock heated. It thus seems that 500 million years ago all these separate L chondrites experienced a common heating event that caused a loss of the ^{40}Ar gas and a resetting of the Ar–Ar clock. They must also have been part of the same parent object at that time. The exposure and Ar–Ar ages are evidence that members of the large chondrite classes came from one or two objects in space.

Origin of chondrites

So what were the objects from which the chondrites are coming? A handful of meteorites, mostly chondrites, were observed sufficiently well during fall that their orbits could be determined. The orbits resemble those of the NEAR-EARTH ASTEROIDS, coming within about 0.9 AU of the Sun and going out to the main ASTEROID BELT at about 2.5 AU (1 AU, the 'astronomical unit', is the distance of the Earth from the Sun, 150 million kilometers). The relationship between comets and asteroids is unclear, and as many as half the near-Earth asteroids could be extinct comet nuclei, but many could have come from the main asteroid belt.

The spectrum of the sunlight reflected from the surface of asteroids provides clues to their surface composition. Over 2000 asteroids have now been sorted into classes in this way, and many appear to resemble meteorites (table 2). However, asteroids with spectra resembling those of the ordinary chondrites, the chondrite class that dominates the Earth's meteorite flux, are very rare among the asteroids. Perfect matches are found for less that 1% of asteroids, and even if one assumes that some form of space weathering is affecting the asteroid surfaces, then less than 11% of the asteroids could be the source of the Earth's major chondrite classes. There are essentially two factors that determine which meteorites reach the Earth besides the abundance of their parent asteroids in the asteroid belt. These are the orbital mechanism for transferring objects from the asteroid belt to Earth and the Earth's atmosphere. Passage through the Earth's atmosphere destroys most of the fragile CI and CM meteorites but leaves unscathed the tough ordinary chondrites. Nearly one-half of the classified asteroids in the main belt have spectra resembling those of CI or CM chondrites while only a few per cent of meteorites reaching the surface of the Earth are members of these classes.

We think that most of the ordinary chondrite classes are coming from single parent bodies, and spectral data show these objects to be rare in the asteroid belt. Recently it has been suggested that the H chondrites are coming from asteroid 6 Hebe, the '6' indicating that it was the sixth asteroid discovered. This 200 km object not only has a surface spectrum similar to that of H chondrites, mixed with some related IRON METEORITES, but also is located in space where both Saturn and Jupiter exert a strong periodic gravitational influence that could send meteorites from Hebe to Earth.

If we assume, as seems likely, that the various chondrite classes are coming from different asteroids, then

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Table 2. The asteroid classes, their relative abundance and meteorite matches.

Class	Abundance (%)	Meteorite match[a]
D	6.2	IDP
P	4.3	IDP
C	22.8	CI,CM
T	1.3	Sulfur-rich irons
B+G+F	9.1	CI,CM
Q	0.41	H,L,LL
V	0.41	HED
R	0.10	?
S (IV)	11.0	Lod, Win, OC, irons
S (others)	25.9	Pal, Ure, Bra, Lod, Mes, Win, Ste
A	0.71	Pal,
M	4.3	Irons, EC
E	1.3	Aub

[a] Meteorite classes most closely resembling the asteroid class. The chondrite classes are H, L, LL (ordinary chondrites, OC), CI, CM, CV, CR, CO, EH and EL (enstatite chondrites, EC); Win, winonites; EC, enstatite (EH and EL) chondrites; Bra, brachinites. Other classes: Ste, Steinbach; Mes, mesosiderites; HED, howardites–eucrites–diogenites; Aub, aubrites; Ure, ureilites; Pal, pallasites; Lod, lodranites; IDP, interplanetary dust particles.

how did the different classes originate? How did their parent asteroids have different surfaces? This is equivalent to asking how the chondrules in the meteorites formed and how the metal and silicate proportions came to differ from class to class. Most scientists argue that chondrite formation and metal–silicate separation occurred in the NEBULA, that lightning or other pulses of energy shot through the nebula dust to produce chondrules and that the metal and silicate grains swirling around in the nebula became separated, perhaps by aerodynamic sorting by the gas or perhaps by some other process. However, the present writer has suggested that both chondrule formation and metal–silicate separation occurred on the surfaces of asteroids. I have suggested that chondrules formed by impact and that metal and silicate grains became separated as gases from the interior of the asteroid, mainly water, passed through the dry surface layers, size- and gravity-sorting chondrules and metal, and adjusting their relative proportions, as they escaped to space.

So the origin of meteorites is essentially the same as the origin of asteroids. The nebula from which the Sun formed fragmented from the larger interstellar cloud and underwent gravitational collapse to produce the proto-Sun and a number of rings of material that quickly coalesced into planets. At the location of the asteroid belt, 2–3 AU from the Sun, the gravitational forces from the major planets (Jupiter and Saturn) were so strong that coalescence was prevented and a large number of tiny PLANETESIMALS formed. Some of these grew by ACCRETION but most fragmented by impact to form the asteroid belt much as we observe it today.

Many of the asteroids contained enough of the radioactive isotope of aluminum, ^{26}Al, that large amounts of heat were generated and they melted to produce the many igneous classes of meteorite. The daughter product of ^{26}Al decay, ^{26}Mg, has been found in aluminum-rich phases of certain meteorites. However, some chondrites were heated without melting, and many were not heated at all. Chondrites are very clearly primitive early solar system materials. Just to underscore this point grains of diamond, graphite, silicon carbide and aluminum oxide have been found in chondrites that have isotopic properties indicating that they were not produced in our own solar system but were ejected from the outer atmospheres of a variety of stars. They are presolar, INTERSTELLAR GRAINS. Thus, while chondrites are widely regarded as heralds bringing us information on the early solar system, in a very real sense they are a connection between our laboratories and processes occurring in interstellar space and distant stars

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