SECTION 10: METEORITES AND ASTEROIDS

10.1 Meteorites

Meteorites are solid objects that have fallen to Earth from space. Thousands of pieces of meteorite are known and are classed into three broad categories; stones, stony-irons and irons. Of all the meteorites, the irons are easiest to identify with an extra-terrestrial origin, as they are unlike any terrestrial rock. The stones on the other hand can look very much like earth rocks and are hence very difficult to spot with an untrained eye unless you are lucky enough to see the fall itself. Irons have high densities of about 7.5gcm^{-3} and are composed primarily of metals (iron and nickel). Stony meteorites vary in density from 2.3gcm^{-3} for the most highly oxidised and volatile rich, to 4.0gcm^{-3} for the most metal rich. They contain between 0 and 30% metal grains within a body of silicate minerals and are separated into two groups, the chondrites and achondrites. The achondrites are generally of igneous origin whilst the chondrites have never experienced melting. The stony-irons, as their name suggests, are made of nearly equal amounts of metal and silicate with densities around 5-6gcm^{-3}.

Our meteorite samples are split into two categories - the falls and the finds. Falls are those meteorites we actually see fall and then recover by tracing their trajectory and tracking down its point of contact. Finds are those that were not seen falling and have simply been 'spotted' as extra-terrestrial rocks lying on the ground. An interesting dichotomy between falls and finds is seen, highlighting the difficulty of distinguishing between stones and terrestrial rocks.

Table 10.1 Classes of falls and finds.

	Stones	Stony-irons	Irons
Falls	95.7%	1.1%	3.2%
Finds	52.3%	5.4%	42.1%

The falls probably represent more accurately the true population of meteorites close to the Earth. Many of the stones that have fallen to Earth and were not observed to fall are likely to be lost completely, unless found in a remote place such as Antarctica, where many finds are collected. The percentage of iron finds reflects how easy it is to identify these as being of extra-terrestrial origin.

10.1.1 Irons

The iron meteorites are classified according to their nickel content, crystal structure and related parameters. The two main minerals in iron meteorites are the iron-nickel alloys kamacite (iron and low-Ni) and taenite (iron and high-Ni), and three classes of iron meteorite are based on the relative abundance of these minerals.

Hexahedrites (H): <~6% nickel. These do not have a high enough Ni content to nucleate formation of taenite and are therefore almost pure kamacite. When these are polished and etched, systems of fine parallel lines are revealed. These are called Neumann Lines, caused by an alteration of the crystal structure within the kamacite crystals as a result of strong shocks applied to the meteorites when they were at low temperatures. The strong shocks were probably caused by impact collisions.

Octahedrites: These are the largest and most diverse iron class and contain more nickel than the hexahedrites (~6-14%). Both kamacite and taenite co-exist in oxahedrites. When these are polished and etched, they show a multidirectional banded pattern due to the intergrowth of kamacite and taenite called the Widmanstätten structure. The large crystals indicate long cooling times, suggesting that the materials were buried deep inside parent bodies. The octahedrite class is further subdivided into 5 smaller classes according to the width of the kamacite band in the Widmanstätten structure.

Ataxites: >16% nickel. These meteorites are made up almost entirely of taenite and show no structure to the naked eye when polished and etched, although a very fine Widmanstätten pattern does exist.

The iron meteorites are also classified according to chemical composition, i.e. the variation of gallium and germanium content. This is too complex and unnecessary for our purposes. If you are interested, look up the overview in McSween.

10.1.2 Stony-irons

Most of the stony-irons fall into two distinct groups with different internal structures. The **pallacite** group is the larger of the two and has a continuous matrix of metal surrounding large olivine grains. They are dominated by kamacite, taenite and olivine with other trace minerals, and may well represent mantle rocks from its parent body or bodies. There is a strong bimodal distribution of olivine composition in pallasites which suggests that there may have been two parent bodies for these meteorites. The other group is the **mesosiderites** and contain chunks of metal in a silicate matrix. The silicates are made primarily of plagioclase and pyroxene, and appear to be crustal in nature. It is possible that they are related to the eucrites and howardite achondrites.

10.1.3 Stones: the chondrites

The chondrite class was originally defined as those meteorites containing small spherical beads of glass known as chondrules. The class now includes meteorites with chondrules and meteorites that don’t but which look like those that do. None of these meteorites have undergone differentiation, and can be split into several sub-categories according to its total iron content. The total iron content is the sum of iron present in both reduced and oxidised states. The reduced iron is basically pure metal, whilst the oxidised iron is usually FeO, and obviously found in silicates. So, a meteorite with lots of silicate may have little metal iron, but lots of oxidised iron and so may still have a high total iron content. The different classes are split into the following:

1. E: the dominant silicate is enstatite (a pyroxene) with little or no olivine present. Enstatite chondrites have two subclasses, EH (high total iron content) and EL (low total iron content).
2. Ordinary: the vast majority of chondritic meteorites have significant FeO content and significant amounts of free metallic iron. There are several sub-classes; H (high iron content), L (low iron content) and LL (low-low iron content). The L class is the more common of the three. Olivine is present in all ordinary chondrites and increase in content from H through to LL, as does the FeO content. Pyroxene tends to decrease as olivine increases.
3. C: the C stands for carbonaceous. These have the highest FeO content of the chondrites and are the most volatile rich. All of the C-type chondrites have a total iron content at least as high as the H chondrites. They are the lowest temperature condensates and probably formed in a very cold part of the solar system. The reasons behind this particular assumption include 1) they have unusually high abundances of volatile compounds, 2) they have low densities, 3) they are rich in organic compounds which would have been driven off by heating, 4) they seem never to have reached temperatures above 500K. Carbonaceous chondrites are sub-divided into four groups. The CI type have compositions closest to solar abundances. They have high volatile contents including water at 8-22% in the form of water of hydration (i.e. water bound in minerals). They have a low density of 2.2gcm^{-3} compared to other chondrites of ~3.6gcm^{-3}. They have never been subjected to high heats or pressures, but almost all of them show brecciation probably through the impact process. They have no chondrules - it is possible that the CI’s formed at a time when there were no chondrules formed themselves. The other three classes do have chondrules and progressively less water. CM’s and CV’s have between 2-16% bound water with CO’s only having 1%. CO’s rarely take on a brecciated form which means that they have undergone little impact events. CV and CO both contain metallic iron where as CM and CI have no, or almost not metal. The CM and CI chondrites do have higher contents of FeO however, in fact they have more than any other chondrite, and tend to have more volatile elements than the other carbonaceous chondrites. CI’s seem to have more total iron than the other CC’s.

So, the sequence of total iron concentration is, from the lowest, LL-EL, L, H-CV-CM, CO, CI, EH. The chondrites vary physically as well as compositionally and there is a 6-grade petrological scheme to cover the different types.

1. No chondrules: very fine-grained and opaque matrix material - these are probably the most primitive. They contain 3-5% carbon and 18-22% bound water, although there is evidence that up to half of this is from terrestrial contamination.
2. Contain chondrules in a matrix with significant amounts of opaque minerals. The silicates, sulphates and metals are not in equilibrium with one another. There is little or no metal, no taenite. The compositions of olivine and pyroxene vary considerably. The abundances of carbon and water are less than 1. (0.8-2.6% and 2-16% respectively).
3. Textures are sharply defined. Silicates are not in equilibrium, but the metals and sulphates are. Both kamacite and taenite are present, carbon and water concentrations are decreasing.
4. Chondrule boundaries are blurred. Silicates are now close to being in equilibrium with one another. The compositions of olivine and pyroxene do not vary so widely and there is no water present and only traces of carbon (<0.2%).
5. Chondrule boundaries become more highly degraded. Silicate phases develop coarse crystals. The matrix has been recrystallised and the olivine and pyroxene compositions do not vary.
6. Chondrules are rare and difficult to see. Most highly metamorphosed of the rocks. It is the type with phases most in equilibrium with one another. They are so thoroughly recrystallised, that they are close to the border of being achondrites, but never quite reached the stage chemical differentiation.

Of the different classes of meteorites, the E’s fit mainly into grades 4, 5, & 6. H are mainly grade 5 & 6. L and LL are most usually found in 6 although some are found in 3-5. CV’s have grades 2 and 3 only. CO are mainly 3, with a couple falling into grade 4. CM is only 2 and CI only 1.

Table 10.2

←Aqueous	**Petrologic Types**	Thermal→

	1	2	3	4	5	6
Carbonaceous	CI					
		CM				
			CV			
			CO			
Ordinary			H3	H4	H5	H6
			L3	L4	L5	L6
			LL3	LL4	LL5	LL6
Enstatite			EH3	EH4	EH5	EH6
			EL3	EL4	EL5	EL6

Most asteroidal and cometary bodies have spectra very similar to CC's and so it is likely that we see only a few percent of the actual number of CC's from the solar system in our meteorite collection. They are weak and therefore most probably break up upon entering the atmosphere.

10.1.4 Stones: the achondrites

These appear to have experienced such high temperatures that they have been partially molten at some point, and hence undergone chemical differentiation. They almost totally lack metallic iron and fall into several sub-categories.

1. Aubrites: the dominant mineral is enstatite. They have low FeO and CaO contents.
2. Ureilites: low CaO content. Similar FeO content to H chondrites. Some have a high carbon content and have undergone severe mechanical shock.
3. Howardites and Eucrites: dominated by pyroxene and plagioclase. Their bulk compositions are similar to basalts and are therefore sometimes referred to as basaltic achondrites. They have a high CaO content.
4. Diogenite: CaO similar to aubrites.

The howardites, eucrites and diogenites have large amounts of FeO, and a wide variety of CaO contents. The eucrites appear to be prime examples of lavalike basaltic igneous rock, which sometimes shows a bubbly texture like lava flows on Earth (vesicular texture). They may well be examples of lava flows extruded onto the surface of some parent body. Scientists even believe they know which parent body they came from - 4 Vesta. They make this claim on the basis of spectroscopy, as the surface of Vesta is the only large asteroid with spectral properties similar to those of eucrites. Vesta does have a very large 460km diameter crater in its side (Vesta is only 458×578km) and this may have been the mechanism for the eucrites leaving Vesta.

A minor, but very important class of achondrite are those belonging to the Shergottite, Nahklite and Chassignites, or the SNC meteorites. They are extremely young compared with other igneous achondrites (1.3Gyr compared to >4Gyr) and have trace gases and nitrogen with very similar isotopes and elemental abundances to the atmosphere of Mars. These are the Martian meteorites believed to have been ejected from the surface of Mars by a large impact. Similarly, some achondrites have been found to be indistinguishable from returned lunar samples, and so it seems that for many years before the Apollo missions, we had in fact touched the Moon.

10.2 Asteroids

Asteroids are believed to be the parent bodies of many of the meteorites we have in our collection. They are small, no larger than 1000km in diameter with the majority being far smaller than that. The field of asteroid research has blossomed in recent years with the advent of new technology and even a flyby by a spacecraft en route to Jupiter. Our knowledge of asteroids has hence grown amazingly fast and will continue to do so for the foreseeable future (look out for the NEAR mission asteroid rendezvous next year).

10.2.1 Asteroid classes

Asteroids have been split into several groups based on their colours. The colours of asteroids are obtained by measuring the asteroids magnitude through particular broad band filters, the most common of which are the U (ultra-violet), B (blue) and V (visual) filters (used extensively by astronomers). The colour of the asteroid is given by the difference between its magnitude in two of these bands. For example, the B-V colour is its magnitude in the B filter minus its magnitude in the V filter. So, a small value of B-V would indicate a bluer asteroid, a higher value a redder asteroid.

FIGURE 10.1 (Fig 3.2, Kowal)

The main asteroid groups in use at the moment are:

1. C-type: these have more bluish colours with flat, more-or-less featureless spectra, similar to the carbonaceous chondrites. The largest asteroid of all (Ceres) is of this type.
2. S-type: these have a reddish colour with spectra similar to the stony meteorites. Achondrites appear to be related to the S-type asteroids, as do some of the chondrites. Most of the asteroids observed fall into the C or S type.

3. M-type: the “M” comes from “metallic” and have spectra that are similar to the iron meteorites. There are only a few M asteroids known correlating well with the number of iron falls observed.
4. E-type: mainly enstatite in composition
5. R-type: these have redder spectra than other asteroids
6. U-type: unclassified.

Show Figure 4.1 of Kowal

There appears to be a systematic trend in the surface composition of asteroids as we pass through the belt. The inner part of the belt appear to be mainly the S-type asteroids and as we go to the outer regions of the belt they become progressively more C-type. In fact from the inner to outer regions of the belt, the percentage of the total population of S asteroids decreases from 60% to 15% whilst the C-types increase from a mere 10% to 80%. Overall ~75% of asteroids are C-type and 15% S-type. Some say that this separation of types within the belt argues against the theory that the asteroids were formed from a disintegrated planet, as in that case, the different types would be more evenly distributed throughout the belt. The current idea of the formation of the asteroids is that they built up in the same way that the major planets did - either by condensing at the same time as the Sun or by the gradual agglomeration of particles and planetesimals left over from the Sun’s formation. The asteroids, although in a stable orbit, were probably prevented from forming one large planet such as Mars due to the gravitational perturbations of Jupiter.

The original asteroid belt probably contained a lot more mass in its early days. High velocity impacts may have shattered some asteroids, ejecting material out of the belt, to cause impact on other bodies, or to leave the solar system or to join other asteroid groups such as the Atens, Apollos or Amors (see later). Most of the smaller asteroids we see today were one part of a larger body or bodies that underwent catastrophic fragmentation, most likely due to impact. We do have evidence that impact/collisions between asteroids have occurred. The close up photos we have of asteroids all show cratered surfaces, as do the moons of Mars believed to be captured asteroids themselves. These impacts cause the asteroids to have a regolith layer, just like our Moon. Over many years, this material would be compacted down to form breccias - many of the meteorites we retrieve are brecciated and so most likely were part of this compacted regolith.

To best highlight how much we know about asteroids (or how little depending upon your point of view), we’ll go through a few of the best known asteroids.

	Diameter (km)	Mass (g)	Density (gcm^{-3})	Rotation Period (h)
1Ceres	940	1.17×10^{24}	2.7	>9
2 Pallas	559×525×532	2.16×10^{23}	2.6	---
4 Vesta	576	2.76×10^{23}	3.3	5.34

Show Figure 4.5 of Kowal

1 Ceres. Ceres contains about one-third of the mass of the entire known asteroid belt. It’s spectrum is pretty flat and featureless, reminiscent of the carbonaceous chondrites. At longer wavelengths however, an absorption band was seen at 3µm, produced by water of hydration (water bound in mineral structures). The light curve of Ceres does not change much over it’s period of rotation indicating that it is quite spherical and uniform in both colour and albedo.

2 Pallas. Pallas has a very similar spectrum to Ceres. It’s orbit is inclined to the ecliptic by 35⌖ and would not have accreted there during formation. Therefore it must have got there by collisional effects or gravitational perturbations from larger bodies.

4 Vesta. Vesta seems to be the only asteroid with a basaltic surface. It must therefore have undergone considerable heating and melting some time in its past. However, Vesta has an average diameter of only 576km which is far too small to have been heated by typical processes such as heating through radioactive decay or gravitational collapse. There are also asteroids much larger than Vesta that do not appear to have undergone such a melting episode. It is the brightest asteroid, reflecting 40% of the Sun’s light, compared to Ceres which only reflects 9%. Recently, another asteroid, an Amor, has been found to have the same spectrum, and so a new-class of asteroid, the V-types has been created. Vesta’s surface is not homogenous as it’s reflected light varies over time. Hubble imaged Vesta showing a large impact basin - it’s difficult to understand how Vesta survived this impact. Vesta may be the source of the eucrite meteorites.

So, why are asteroids so important to study, apart from the fact that they, like the meteorites, have the potential to give insights into the earliest stages of solar system evolution? It is an asteroid that is believed to have caused the extinction of the dinosaurs 65 million years ago, and which are perhaps responsible for other minor extinctions in the past as well. These asteroids obviously had Earth-crossing orbits, and there are others out there. The majority of the asteroids are situated in the range of 2.1 to 3.6 AU with a handful of groups known to have unusual orbits. In particular, the Aten group have a semimajor axis <1AU and which orbit the Sun in less than a year. The Apollos are of more interest as they are the Earth crossing asteroids which may well cause us some trouble one day. Also of interest are the Amors, which do not yet cross the orbit of the Earth, but have perihelia very close (~1.3AU). Perhaps their orbits will one day become

Earth-crossing through gravitational perturbations on their orbits. 200 Apollos have so far been discovered, with an estimated 1500 objects larger than 1km believed to exist in total.

Show figures 7.1 and 7.4 of Kowal

It is estimated that the Earth is hit by an asteroid >1km diameter every 300,000 years. For comparison, Meteor crater was formed 50,000 years ago but was caused only by a 100m diameter object. These impacts probably happen every few thousand years or so, and are less devastating, although if one landed in the centre of a city, thousands of people would be killed. These would probably not be detected before they hit.

Reference List

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*** NOTE*** There are several other meteorite books in the library, but beware - the older the book, the more out-of-date it will be, and some things may have changed dramatically since they were written.