13. Asteroids and Meteorites

Meteorites

It is usual to distinguish between meteorites which are meteoric bodies that have fallen to earth, and their originating meteors. Meteorites themselves are divided in "Falls" and "Finds":

- Finds: are meteorites that have been simply found in the field with no idea necessarily as to when they arrived or whence they came.
- Falls: are bodies where the arrival is noted - either visually or by radar tracking - followed by their recovery. This group is very small. Several tens of meteors have been tracked on entry but only a handful have been recovered.

The falls are important in that they give information on arrival direction, and thus enable us to say from where in the solar system they might have originated. If they are associated with a comet, or asteroid, for example, they might be expected to be residue from that body. If we can consider a meteorite we find to be an example of the primordial matter of the solar system, then the "falls" enable us to map the distribution of this. Most falls so far have mapped back to earth-crossing orbits going back into the asteroid belt, suggesting an asteroidal origin.

Types of meteorites

There are several different types of meteorite:

- Stones (52.3% of finds) 0-30% metal, sulphides and silicates, a mixture of textures.
- Stony-irons (5.4% of finds) 50:50 metal/silicates
- Irons (42.1%) Have densities of order 7.5 $\times 10^3$ kg m^{-3}, usually tough Fe/Ni/Co

The stones are either of igneous origin (achondrites) or have never been melted (chondrites). The "chondrites" are named after the "chondrules" which are small glassy or crystalline beads of material which are found embedded in them. Nickel seems ubiquitous, and its presence is a good check for meteoritic material.

When found meteorites often have a fusion crust, then a glassy surface layer. The surface is usually partly ablated away by the frictional heating due to passage through the atmosphere, the fusion crust being the remains of this melted material. The heat causes a heat pulse as well as vaporization. One can estimate the effect by seeing how much heat one gets by conversion of the Kinetic energy to heat. The maximum encounter velocity v_{max} is given by (see section on cometary encounters):

$$v_{max}^2 = (2.41\ v_0)^2 + v_e^2$$
$$= \text{c. } 73\text{UP>2}$$
$$= \text{c. } 73.28 \text{ km s}^{-1}$$

where v_0 is the Earth's orbital velocity and v_e is the Earth's escape velocity. Most bodies actually enter with a smaller relative velocity - around 40 km s^{-1}.

At v_{max} the kinetic energy density is 5.2 10^9 J kg^{-1}. The average energy needed to melt rock is about 1.2 10^6 J kg^{-1}, while the energy to crush a rock is only about 10^9 J kg^{-1}. The fastest ones therefore tend not to survive. But "typical" 30 km s^{-1} arrivals at a low angle of entry can survive by ablation and thermal inertia. One gets a range of break-up and survival depending on speed and material. At the ground there are some supersonic and some subsonic impacts. Some break upon contact.

Some bodies at shallow angles also "skip out" of the atmosphere. Occasionally there are large explosions due to very large bodies like the "Tunguska" meteorite which blew up in the air over the Siberian forest on 30th June 1908. The explosion had an equivalent force of megatons of TNT, and the explosion destroyed 2,000 km^2 of forest.

There is actually one incidental use of meteor ablation trails, in the exploitation of the echoes these give for "meteor radars". These are used to measure neutral winds in the height range 90-120km, by tracking ge 90-120km, by tracking the ionised ablation trails, which follow the neutral atmosphere's motion after formation.

Some information can be derived about crushing strengths by tracking break-ups. One estimates the dynamic pressure at the altitude and velocity of the break up and this is related to the rock strength.

Classifying meteorites

A number of different ways have been devised of classifying meteorites. They are often divided into "ordinary chondrites" (which seem to be associated with Earth-crossing asteroids, replenished from the main belt) and "carbonaceous chondrites" which seem to be similar to bodies in the main asteroid belt, but could also be linked to cometary cores.

The chondrites are often broken into classes using the Fe:FeS ratio v Fe:FeO and other ratios of material. Another classification is in terms of the FeO content of Pyroxene v FeO in the Olivine. These types of classifications are usually tied in with attempts to group the bodies according to origin.

Some of the achondrites (igneous stony meteorites) are though to be lunar fragments - and we have already see under "Mars" that there is a group (SNC) of meteorites thought to originate on Mars. The usual way of assigning such groupings is by measuringthe isotopic abundances, the proportion of volatiles and the radio-isotope content. (See also the description of identification of the SNC meteorites.)

All these compositional analyses give clues to the origins of the material and enable theories to be developed concerning relationships between types, and to primordial material. This has proven complex and as yet far from conclusive, with too many unknowns (see pp. 330-333 Lewis). Certainly there is some evidence of a connection often to the asteroid bodies, however.

Some meteorites are more important than others in terms of the information they have provided. The **Allende meteor**, for example, has been a particularly important find and extensively studied, partly because it is so large, and partly because of its interesting structure. The more it has been studied, though, the more ambiguous have seemed the results from those initially obtained. The Ar^{40} dating puts its age at 4.6 Gyr, which places its creation at the very begining of the solar system. It has a number of interesting small objects or inclusions embedded in a background rock composed originally of fine mineral dust. Two types of inclusion are the CAIs (Calcium and Aluminium Inclusions) and "chondrules" of pyroxen and olivine. Conjecturing how these inclusions attained the chemical compositions they have, and how the material formed together, has lead to much debate about the early state of the proto-solar nebula, where itis assumed the Allende meteor formed.

One paormed.

One particular interesting piece of information we have come across before when we discussed the formation of the solar system. This comes from the fact that the meteor has an "excess" of Mg^{26}. We can estimate from the "normal" isotopic ratios of Mg^{26}/Mg^{24} the amount of Mg^{26} expected accompanying the Mg^{24}. If there is more this is probably the result of radioactive decay of Al^{26}. Al^{26} is not normally found in any large quantitues in proto-solar nebulae because its half-life is so short, so it does not survive with the other high atomic mass products injected into interstellar space by first and second generation stars. It is, however, formed in supernovae, where large energies form more exotic atoms, and can inject them into nearby regions of space. The fact that ther is an Mg^{26} excess in the Allende meteor (and others of its type) suggests that there was more than the expected amount of Al^{26} in the early nebula when the meteor was formed. This, in turn, suggests that there was a nearby supernova at or near the same time. There has been a suggestion that this supernova may even have been the trigger for the formation of the solar system in the first place, since theories of solar system precipitation from the pre-system nebulae usually requires some trigger and one possibility is the shock wave from a superk wave from a supernova explosion.

Asteroids

Asteroids have been classified mostly upon their visual appearence-albedo and spectral classification of reflected and emitted radiation. There are a number of distinct classes, but the two largest classes in the main group of asteroids are the "C" and "S" types. The C-class asteroids have very low albedos-that is they appear extremely dark, as low as 0.02 and usually 0.05-0.01. It is difficult to see what natually occuring mineral apart from Carbon can be the cause of this, so these are generally believed to be carbonaceous in nature (and probably related to carbonaceous chondrite meteorites.) The S-type asteroids have albedos several times higher than the C-type asteroids, and because of their spectral characteristics are thought to be Silicon rich. These have similar spectral characteristics to stony meteorites (chondrites and acondrites).

The albedo distribution of the different classes of asteroids are shown in the following figure. The x axis is albedo, different shadings are the different classes as shown by the key in upper right corner. The different classes are overlaid not stacked. (From Lewis)

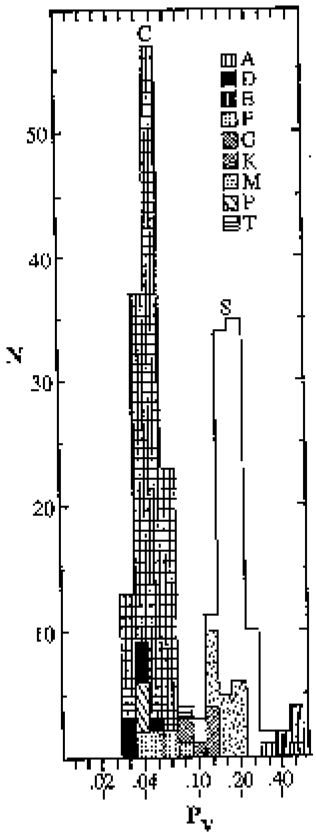


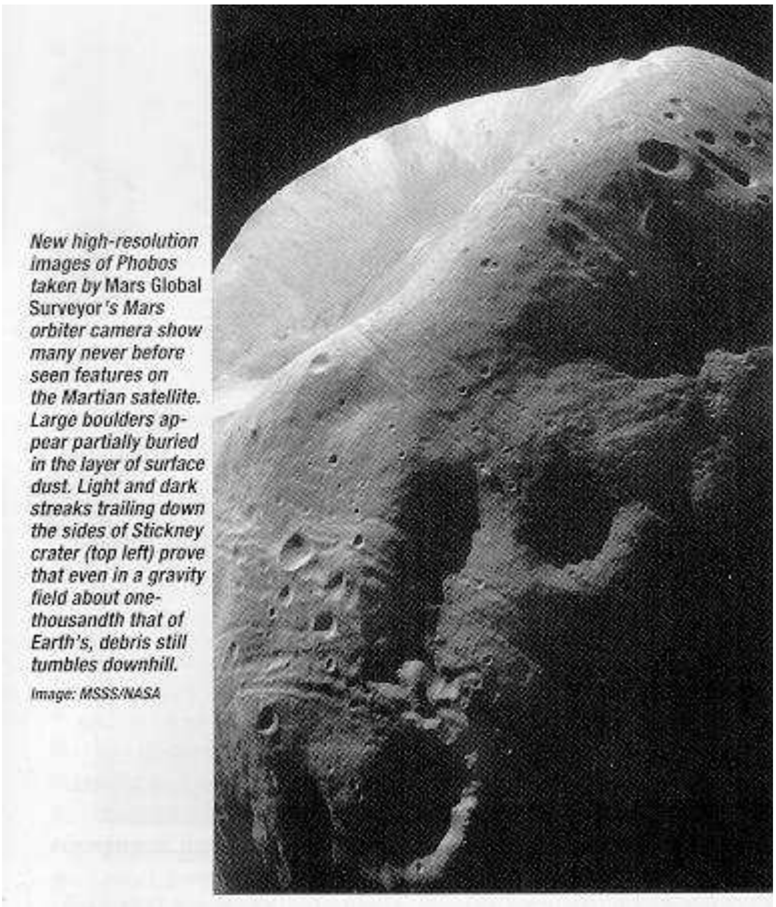
Figure VIII.32 Relationship of asteroid taxonomic class to albedo. Individual classes are overlaid, not stacked, in this diagram.

It is found that the different classes of asteroids tend to be dynamically separate too- that is different classes occupy different orbits around the asteroid belt. Thus S-typeroid belt. Thus S-type asteroids peak near the inner edge of the main belt-from 2-2.5 AU from the sun. The C-type asteroids occur further out, with a peak near 3-3.1 AU.

A number of recent advances have been made in our studies of asteroids, including the first photographs close up. Generally the small and medium-sized asteroids are irregular in shape, and with numerous small craters. The Galileo space probe managed to get a good photograph of 951 Gaspra, which showed it to be a surprisingly smooth irregular object 10-12 km long, not unlike Deimos and Phobos. It also photographed Ida, a somewhat larger asteroid about 60km across and apparently accompanied by a tiny satellite, Dactyl. Gaspra and Ida are silicate-rich S-type asteroids typical of the inner part of the main belt. Both were mottled with subtle colour variations that suggested different rock types at different locations.The NEAR spacecraft has also imaged 253 Mathilde, no easy task as it is a C-type asteroid (believed to be rich in Carbon, and typical of the outer belt) with a very low albedo. It reflects only 3% of light falling on it (twice as dark as charcoal), and it was encountered at twice the Earth's distance from the Sun. It is an irregular object about 60 by 50 km in size and with a heavily cratered surface. Some of the craters are surprisingly large - it is difficult to see how one, 20km across, did not cause the body to be split in two!

The NEAR spacecraft has also recently (Dec 1999) reached the asteroid EROS and taken a series of photographs prior to going in to orbit about it. Other asteroidal shapes have been measured by radar. Delay Doppler images have enabled maps to be made of asteroids that came close enough to the Earth for the large radar installations like Arecibo to get good enough echoes. (This has restricted it to NEOs-Near Earth Objects). An example is 4179 Toutatis (a 4.2km long NEO) which is found to be so irregular it looks a lot like two components in close contact (see image below).

Some idea of the shapes of objects further away have been obtained from their light curves, though here the problem is always distinguishing between albedo and shape variatioons. There is some indirect evidence from imaging of asteroid-like bodies such as the Martian moons or the smaller moons from the gas Giants, which may be captured asteroids, or closely related to them.



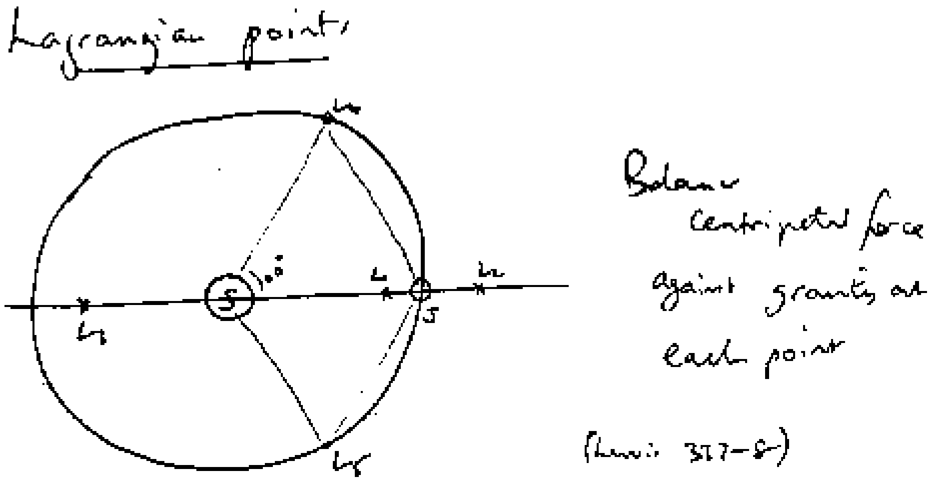
This image for example shows part of the surface of Phobos. Recent Mars Global Surveyor thermal cooling results indicate it could be covered by up to a meter of dust.

The asteroids do not occur homogeneously throughout the Mars-Jupiter gap. In fact there are groups which do not fall in the gap at all. The majority do, of course, and these are called the "se are called the "main belt" asteroids. Generally these occupy the orbits with semi-major axes from 2 to about 4 AU (with some large gaps between 3.2 and 4 due to resonance interactions with the gas Giants).

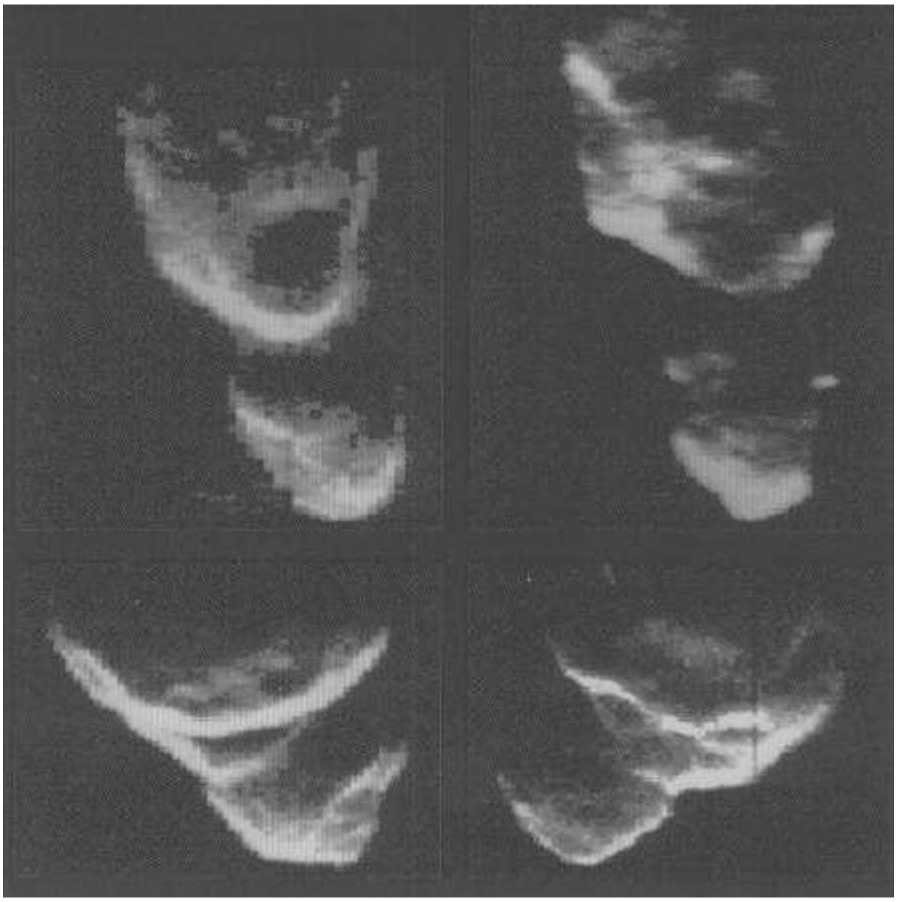
The distribution of asteroids by distance from the Sun. The x axis is the semi-major axis in AUs. The y axis is number of bodies.

There are asteroids which come inside Mars' orbit, however. Those which approach Earth are known as NEAs (Near-Earth Asteroids) or NEOs (Near-Earth Objects). Those which come inside Mars but do not cross the Earth's orbit are known as Amors (after the first of the group discovered). These have perihelion distances inside 1.3 AU (but outside 1.017, Earth's aphelion). Those which actually cross the Earth's orbit (though with a >1.0) are called the Apollo group (again after the first of the group discovered). There is even a group which has a<1.0, called the Aten group, and in 1998 for the first time was discovered an asteroid that orbitted entirely inside the Earth's orbit (i.e. aphelion < 1.0 AU).

The first asteroid found, and the largest, is Ceres (1020 km diameter), the next being Vesta (550km - both measurements being +/- 10%). A recently discovered sub-group, possibly linked to the Kuiper belt objects, are the Centaurs (the first of these, Chiron, was discovered in 1977.) These move in orbits within tve in orbits within the region of the outer planets. They are of a size comparable with the larger asteroids, hence much bigger than a typical cometary nucleus. There are also the "Trojans" (so-called because they are all named after Trojan heroes) in Jovian Lagrangian point ("leading" and "trailing") orbits:



There are several pieces of evidence that asteroids "clump" or travel in pairs and/or groups. The imaging from the "Galileo" probe of 253 Ida's small companion did not come as a total surprise as there had been some suggestion that other bodies' light curves showed the light seemed to be occluded at times. This would be at regular intervals, but not at the body's rotational period. Radar studies of 4179 Toutatis show, as we have seen above, that it looks more like two bodies in close contact than one. Here are 4 radar views of it taken at different times.



But perhaps the most widespread evidence is in the fact that impact craters bodies like the Moon and Mars often occur in twos or "sets". Sometimes this is explained as secondary ejecta from a primary impact, or sometimes, that the craters are near geographically, but separate in time. Nevertheless, often the only real explanation is that two or more bodies arrived together. If asteroids, or asteroidal-like bodies are the cause of these craters, this suggests a not-insignificant proportion of them must travel with companions.

We have put the presence of the asteroid belt between Mars and Jupiter in context in an earlier lecture when we discussed the Titus-Bode "Law". The first asteroid was not found until the last century, but a whole host of consecutively smaller and smaller bodies has joined the lists since. About 40,000 bodies are though to exist of greater than 1km size. To study them, the techniques used have been often those we discussed above for studying small satellites remotely:

- mutual interactions give estimates of mass
- measure the time variations of brightness (light curve). This gives the rate of rotation at least.
- measure the visual and i.r brightness - gives estimates of A, albedo, and r, the radius
- spectra of reflected light at different angles (compared to Lab samples --> estimate of material)
- polarization v frequency and phase angle - gives information on the surface material

- radar observations - surface size and roughness
- thermal emissions (properties of the surface layers)
- occultations by stars --> radius

The rotation periods are found mostly to be in the range 7-30 hours. Enough albedos are known to suggest 2 classes (one with a maximum ot 2 classes (one with a maximum of 0.033, the other with a minimum of 0.07 and a maximum of 0.15). The darker ones are possibly carbonaceous chondrite material, the lighter ones other chondrites and achondrites - though this is very speculative.

From their spectra asteroids are divided into a number of classes - 14 are given in Lewis - and tentative guestimates given of the probable surface material. They can also be tentatively compared to meteoritic material to give meteor analogues. The spectral albedo vs wavelength of common materials, as shown here, is compared to asteroidal spectral albedos to make these identifications:

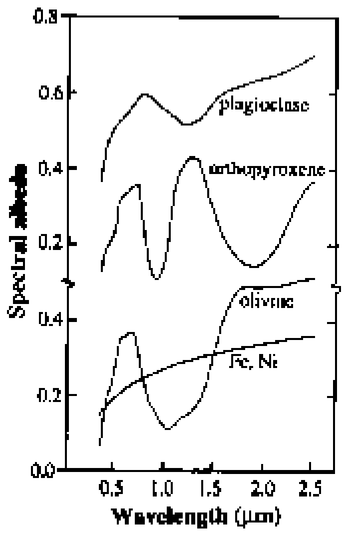


Figure VIII.28 The wavelength dependence of albedos of selected important asteroidal minerals. Note the change of scale (to avoid the confusion of plotting the four curves on top of each other). Metallic surfaces are red but free of absorption bands. Most normal asteroids contain mixtures of these and other, less abundant, minerals, making spectral interpretation more difficult.

Densities, with current information, can only be estimated to within 35-45% (density usually 2-3 10^3kg m^{-3}, and they cannot be sufficiently well distinguished to classify by density. The spectral classes however seem to be distinct, and suggest compositional zoning of the asteroid belt, which ties in with theories of solar system formation, though not all facts fit conveniently.

Asteroids, Meteorites and Comets

Attempts to correlate meteoritic material with classes of asteroids and comets are speculative but have been attempted. We have discussed the correlation a little under "comets", and we shall now look at it a little more with respect to asteroids.

It is certainly true that there are many similarities between some classes of meteorite and some asteroid groups. However, it is difficult to explain generally how asteroidal material can be "ejected" inwards with sufficient energy to reach the Earth - this requires collisions, explosions and resonances.

NEAs (Near Earth Asteroids) do seem linked to short-period comets and in fact 1979 VA has been shown to have been comet Wilson-Harrington 1949 III. Also NEA 3200 Phaeton is the source of the Geminid meteor shower. NEAs have been detected down to a size of 8-9 m diameter, and there seems to be an "overabundance" of sub-100m bodies if asteroidal belt numbers are extrapolated down, which ties in with lunar cratering densities and the number of fireballs seen on Earth.

Further material in Handouts

Further supplementary material was handed out in the lectures to be used as background reading on these topics. This included details of the NEAR asteroid rendezvous mission, latest findings on protoplanetary nebulae (and planets) about other stars, articles on the ALH84001 meteorites, and an article on a current theory that shed-sized comets are hitting the Earth's upper atmosphere several times a day. I will not attempt to repeat this material on the web. Anyone who failed to get a copy in the lectures should see Dr Aylward.