Notes 4: Meteorites, Comets, Asteroids, and other things

4.1 Definitions

Obviously when the solar system formed, there were probably a few bits left over. So not only do planetismals and bits of planetismals remain out there, but they are useful in telling us about the history of the solar system and giving us some information about the formation process. Some of these bits do fall and end up as meteorites in museums, but we also know that they fall and cause craters on pretty much any surface in the solar system. And some of the larger bits end up as satellites of outer planets. Now we’ll look at the meteorites and then we’ll take a look at the other objects out there, namely comets and asteroids, as well as what happens when these objects hit one another (or us).

First a few definitions so that you know what these things are:

**Meteoroid:** Small object in space. This could be a natural or artificial object, a piece of a comet, asteroid, planetismal, or a bit of a planet that has been blasted off into space. Generally these things are much less than a kilometer in size, since if it is larger than that it is usually referred to as something else like an asteroid, comet, etc. We usually don’t detect these until they go the next step.

**Meteor:** When a meteoroid enters the atmosphere, it is then a meteor. This is also known as a shooting star. The trail left behind is also called a meteor. The trail of material can be whitish or bluish in color, though at times yellow, and red are also seen. A particularly bright meteor is called a **bolide**, or a **fireball**. These very bright, and generally large objects, are usually the source of meteorites, though only a fraction of these observed are actually recovered. Some green fireballs are thought to be due to copper.

**Meteorite:** An object from space that hits the ground. There are 3 main types – stony, irons, stony-irons, but more on that in a second.

**Fall:** an observed meteorite fall – so actually seeing a meteor go through the atmosphere and collecting it.

**Find:** a meteorite discovered later on, not necessarily associated with an observed fall. These are usually iron meteorites since they are not eroded as easily as the stony meteorites.

**Parent body:** the object that the meteorite came from.

4.2 Finding Meteorites

Meteorite falls have been observed throughout history with even ancient reports of stones falling from the sky. For the most part it was thought that these things did not actually happen but were considered foolish folktales or legends. Generally any report of a meteorite fall was dismissed by those with an education, so even if someone observed a fall and collected an object, it was usually dismissed as a mistake of an uneducated peasant. It wasn’t until about 1800 that there was some re-examination of the idea of things falling from space. This led many scientists to take another look at all of those mysterious rocks that peasants had gathered years before and they realized that these were unique objects.

Today meteorites are collected from locations all over the earth, but some locations are better than others. Satellite images have revealed locations of impact craters on the Earth that were
previously unknown, and these have produced meteorites. The ice of Antarctica is a very fruitful source of meteorites, since there is quite a bit of glacier deposition of meteorites that have landed on the surfaces of the glaciers in the past. The ocean floors are also full of meteoritic material, since it remains undisturbed for years. Also, if you were to walk outside and look at the ground, or at the grime or grit in the center of a raindrop or snowflake, you’d likely find meteorites. These are caused by meteoritic material that has been reduced to the size of dust particles in the Earth’s atmosphere. And this material continually falls to the surface of the earth.

When people observe a meteorite fall, there are quite a few variations. First of all, the brightness of the meteor will depend strongly on the size of the object. The train of material left as it passes through the atmosphere is similar to a contrail left by a jet in the sky. It is often the case that sound is heard with a bright meteor. Sonic booms are not unprecedented, though some have reported a hissing or sizzling sound. One of the ideas that is often associated with meteor falls is that the object is ultra hot. That’s not entirely true. Meteors are not heated entirely through with most of the heating found on the outer surface. This usually results in a fusion crust, which sound exactly like what it is – the crusty bit on the outside of a meteorite. Usually it is darkened, charred material. Meteor falls are relatively short term events due to the high velocities involved and the relatively thin atmosphere of the Earth. With the Earth’s motion and the meteor’s motion you have relative velocities on the order of 10-70 km/s. The higher velocities can cause complete fragmentation of the object.

How much material falls on the surface of a planet depends on a lot of factors. Also you have to remember that the supply of material is going down – there is less and less material out there that is available to fall on a planet’s surface, so the rate at which material falls on a planet has decreased as the solar system has gotten older. It is estimated that the Earth has about 10 million to a billion kg of meteoritic material falling on the surface every year! That’s a lot of stuff, but of course most of that happens over oceans or in the form of meteoritic dust (micrometeorites). On the Moon, about 4 million kg fall each year. On the Earth there is only about 1 impact a year that causes damage, and a serious damaging impact happens about once every 20 years, though most of the time the impact occurs in the atmosphere (it blows up there). As is usually the case, the larger, more damaging impacts are rarer.

While things can be seen to fall from the sky, we don’t always find them. In fact the types of meteorites associated with “finds” and “falls” is the following -

<table>
<thead>
<tr>
<th></th>
<th>Stony</th>
<th>Irons</th>
<th>Stony-Irons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falls</td>
<td>95%</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td>Finds</td>
<td>52%</td>
<td>42%</td>
<td>6%</td>
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</table>
So what is the real distribution of the types of meteors? It would be the “falls” – meteors collected after observed falls, since those are fresh and not skewed by environmental effects. In general it is just easier to find iron meteorites than stony ones since they last longer and don’t blend in as easily as the stony meteorites with earth rocks.

The fact that meteorites actually come in a variety of types indicate a few things. Obviously like other objects in the solar system, the location of formation influences the composition of the meteorites. For some meteorites we know that the parent body they were part of had been altered through some process (often heating). The fact that there is a type of meteorite made up of a mix of stone and iron indicates that differentiation took place in the parent body. Other meteorites did not get heated since they come to us with volatile material within them. These would be considered as very primitive objects – unaltered since their formation. Also, with some meteorites there is evidence of collisions within meteorites, since some have breccia.

So basically some large objects formed in the early solar system and these objects may have been heated enough to melt the material within them. The siderophile (iron-affinity) elements sank inwards, while the lithophile (crustal associated) and chalcophile (sulfur-liking) elements tended towards the surface. Collisions then caused these large object to break apart, perhaps forming breccias in some cases, and a variety of meteorites that we see today were produced. Other objects that formed may not have had enough mass to heat through or melt the material significantly, at least not to the point where volatile material was lost. These were the sources for other types of meteorites containing volatiles and some rather interesting molecules, as you’ll see.

### 4.3 Types of meteorites

<table>
<thead>
<tr>
<th>Chondrites</th>
<th>Carbonaceous chondrites (CC)</th>
<th>Ordinary chondrites</th>
<th>_</th>
<th>_</th>
<th>_</th>
<th>_</th>
<th>_</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stony</td>
<td></td>
<td>CI</td>
<td>0.7</td>
<td>CM</td>
<td>2.0</td>
<td>CO,CV</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>1.5</td>
<td>H</td>
<td>32.3</td>
<td>L</td>
<td>39.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LL</td>
<td>7.2</td>
<td>Others</td>
<td>0.3</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Ureilites</td>
<td>0.4</td>
<td>Aubrites</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diogenites</td>
<td>1.1</td>
<td>Howardites, eucrites</td>
<td>5.3</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Others</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mesosiderites</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Pallasites</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Irons</td>
<td>IA</td>
<td>Medium and coarse octahedrites</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>IIA</td>
<td>Hexahedrites</td>
<td>0.5</td>
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<tr>
<td></td>
<td>IIIA</td>
<td>Medium octahedrites</td>
<td>1.5</td>
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</tr>
<tr>
<td></td>
<td>IVA</td>
<td>Fine octahedrites</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>Ataxites, etc</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table here shows the main meteorite types (left most column) and the various ways that those types are subdivided, and the percentage of the various types that have been recovered in falls.

The most common type is the **Stony** (95% of all meteorites). As the name implies, these are sort of “stony”, though there is a variety in the type of
stones. The most common is the **Chondrites** (86% of all meteorites). These get their name due to the presence of chondrules inside of them, which are glassy spheres of minerals, about ~.1 – few mm in size. The minerals found in chondrules are olivine, pyroxene, enstatite, etc. These are the most primitive of all meteorites. The chondrites are further subdivided into two main groups, the **carbonaceous condrites** (5% of all) and **ordinary chondrites** (81% of all). The carbonaceous condrites, or CC, are the most primitive of all meteorites since they have the lowest formation temperature. These would have formed at temperature of less than 500 K. These are generally thought to have formed in the area of the outer asteroid belt, at distances greater than 2.5 AU. CCs also have been found to contain volatiles, as well as organic compounds. They are fairly low density as well. Their generally black color is due to carbon (graphite), and they have magnetite around the chondrules, and other minerals in the matrix (the stuff around the chondrules).

CCs are subdivided into various divisions based upon their compositions –

**CI** – contain between 8-22% water. These have a composition that is very close to the solar composition. Also they have no chondrules. These are probably from ice rich parent bodies, and based upon the presence of carbonate and sulfate deposits in them it is likely the parent bodies had some seepage (water motion) which left these deposits.

**CM, CV, CO** – pretty simple, they have less water, more chondrules. There are chemical differences between these types as well, with different amounts of Fe, S, Si, Al, Ca, etc. in them. The CM meteorite from Murchison, Victoria has over 70 extraterrestrial amino acids and other compounds including carboxylic acids, hydroxy carboxylic acids, sulphonic and phosphonic acids, aliphatic, aromatic and polar hydrocarbons, fullerenes, heterocycles, carbonyl compounds, alcohols, amines and amides.

The most common form of chondrites are known as **Ordinary Chondrites** (81% of all). These are the most numerous of all meteorites. They have less water, carbon than the CCs and show evidence of more alterations (chemical effects) in them. These still show that there was not a great deal of heating occurring in them. With less carbon and water, it is likely that they formed closer in to the Sun, around a distance a bit less than 2.5 AU. They are further classified by their iron content and whether it is in the form of iron-oxides, or as pure metal (reduced).

Here are the types of ordinary chondrites:

**E**=enstatite, likely formed in an environment with a temperature around 1300 K. This would have been similar to the environment where the terrestrial planets formed, so the study of this particular type is very important.

**H**=high iron content

**L**=low iron content

**LL**=really low iron content.

These different forms of ordinary chondrites could be due to formations in different environments or from different parent bodies.

The other main group of stony meteorites are the **Achondrites** (9% of all). These have no chondrules – why? Something has apparently destroyed them, possibly through a melting or other processing method. In general they look like igneous earth rocks, like basaltic rocks. It is believed that they originated from a parent body that was strongly heated or melted. This would
also reduce the iron content (it would sink), so that the outer parts of the parent body would become the source of the achondrites. The major groups of achondrites are Diogenites, Howardites, Eucrites, Aubrites, Ureilites. The differences of these are due to the variation in the amount of FeO, Ca-rich minerals, and the ratios of various minerals. It is thought that the large asteroid Vesta may be a source for these meteorites.

The rarest type of meteorites are the **Stony-irons** (1% of all). And as the name implies these are a mix of stone and iron. It is thought that these originated from regions in parent bodies where the rock abuts the metal core, though some have a rather crustlike structure which would not be near the core. So we still have some uncertainty in how these could have formed. There are two main groups of stony irons -
- **Mesosiderites** – chunks of metal in rock
- **Pallasites** – chunks of rock in metal

Sort of a simple way of looking at them, but then again, they are pretty rare.

The meteorites that people usually picture in their minds are the **Irons** (4% of all). The name is misleading since it isn’t just iron, but a mix of iron and nickel. The ratio of Fe:Ni is used to classify them further. The amount of Fe to Ni also determines the types of minerals within them. The two main minerals are kamacite (with relatively low Ni content, 10-5%) and taenite (with high Ni content, 20-65%), and not only does this show a difference in composition, but also a difference in the internal structure of the iron meteorite.

Iron meteorites come in several varieties:
- **Hexahedrite** – have about 5% Ni (so nearly pure kamacite), and these show *Neumann bands*, parallel lines seen inside of the meteorite, thought to be produced through an impact shock event.
- **Octahedrites** – have about 6-14% Ni. These are the largest group of irons and contain both taenite, and kamacite in them. The growth of these crystals is seen in the *Widmanstatten pattern*, the interlaced pattern made up of the taenite and kamacite crystals. Depending upon how the meteorite is sliced open the pattern can be triangular or boxy looking.
- **Ataxites** – have > 15% Ni content, so they are comprised of mainly taenite. These show no internal structures to their crystals, so rather boring.

Other classifications of iron meteorites are based on Ge, Ga, Ir content.

There is a wide range of minerals found in meteorites which include taenite, kamacite, copper, sulfur, graphite, diamond, troilite, pyrite, chalcopyrite, sphalerite, corundum, perovskite, hematite, magnetite, spinel, quartz, calcite, dolomite, gypsum, apatite, olivine, pyroxene, feldspar, plagioclase, orthoclase, zircon, serpentite, muscovite mica, etc. Yes, diamonds!

Where do these objects come from? Most meteorites are thought to come from parent objects that were/are in the asteroid belt. A few falls have been traced back to orbits that can be found in the asteroid belt. Also composition studies of asteroids show surfaces that are similar to meteorites. Some meteoritic material may be from comet-like sources, especially the small stuff like the dust-sized micrometeorites. But it isn’t entirely impossible for larger meteorites to also be from cometary sources – it just isn’t always possible to trace meteorites back to the source.
Along with the asteroid/comet source there are some meteorites that came from the Moon, and Mars. This is based mainly upon their compositions, especially noble gases and isotope ratios within them. Mars meteorites are often called SNCs based upon the locations where the first ones were discovered: Sherghati, India, El-Nakhla, Egypt and Chassigny, Haute-Marne, France respectively. Now it might be more appropriate to call them just MM (martian meteorites). Of the ~24,000 meteorites found on earth, 60 are MM.

While MMs may appear to be a bit of a curiosity, they may also hold some valuable clues to the evolution of Mars. Things got rather heated in 1996 when NASA made an announcement of evidence for primitive life forms located within a Martian meteorite! ALH84001 is the exciting name of the meteorite, which was discovered in Antarctica. The various arguments for the evidence of life include the following -

- Presence of polycyclic aromatic hydrocarbons (PAHs) in the meteorite (but those could be contaminants from the earth, since they seem to have a radial distribution).
- Presence of magnetite, a bio-deposition mineral (comes from anaerobic bacteria), though this could be contamination from the Earth, and others point to a possible non-biological source. In 2002 a follow-up study of the form of the magnetite crystals indicated that the form of about ¼ of the crystals is associated with biological processes. Unfortunately it is not possible to really check this since it would destroy the structure of the sample.
- Objects that look suspiciously biological – or is it just mud? These objects appear to be too small to be bacteria, but could they be an unknown form of nano-bacteria (does that even exist?)

Things don’t really seem to be in favor of this idea at present, though there have been continued studies of MMs to look for better evidence of life (or past life).

There is speculation that some enstatite meteorites may come from Mercury, or another terrestrial planet due to their high formation temperatures. But at this time that is only speculation, and would be rather difficult also given the proximity of Mercury to the Sun.

### 4.4 Comets and Asteroids

**Definitions**

Okay, what is the difference between these two types of objects. The distinctions were much simpler 30 years ago…

- Comets – Icy, small, wild orbits, come from the Oort Cloud
- Asteroids – Rocky/metallic, a few really big ones but many are small, with rather uniform orbits like planets, found in the asteroid belt.

This seemed like a good system, but then something happened that blurred the line between comets and asteroids. This was the discovery of objects thought to be asteroids but which later turn out to be comets (they were discovered when they were inactive and not very comet-like). One of the first of these discovered was Chiron in 1977. This object is found between the orbit...
of Saturn and Uranus, which caused astronomers to label it an asteroid. It is fairly large, about 250 km in size. Later studies showed that its composition was more like that of a comet, and that it had flare-ups, similar to the changes in a comet. So it’s a comet? I suppose so, but a really big one!

Let’s try this definition: an asteroid is something that isn’t a comet. So that would be something that doesn’t flare up, or form a coma, or form tails, or anything that a comet does. If it doesn’t act like a comet then it is an asteroid. Yes, not very precise, but this is astronomy after all. And it’s for the unclear line between comets and asteroids that it is best to talk about these things all together rather than separately.

Of course things got complicated with the discovery of more objects like Chiron, including objects beyond Neptune and some found in other strange orbits that show that life isn’t so simple.

So rather than trying to label things, let’s consider where these things are located and what they are doing – that might be the best way to classify them.

Comets (in the traditional sense of the word) come in two forms -
- Short period - 200 years or less, could come from the Kuiper Belt, or the Oort cloud
- Long period - > 200 years, most likely come from the Oort cloud

Basically the two sources for comets should relate to their orbital periods or motions. The problem is that orbits change, sometimes drastically. So it is possible for a comet coming from the Oort cloud to have its orbit altered significantly enough so that it looks like it actually came from the Kuiper Belt.

Asteroids (mainly rocky, metallic objects – traditional meaning) are usually classified based on their orbits and locations -
- Aten – An Earth crosser, found mainly interior to the Earth’s orbit, about 750 known
- Apollo – An Earth crosser, but with an orbit exterior to the Earth’s, about 4800 known
- Amor – A Mars crosser, about 4050 known
- Asteroid belt (range of distances) – most asteroids are found here – 36,000+, and these can be divided into many different families, based on distance and various orbit parameters.
- Trojans – in L4, L5 of Jupiter, about 5700 or so

And then there are the objects that are “cometary”, they may have compositions similar to comets, but don’t move like comets -
- Centaurs – these are found between Jupiter – Neptune, 450 or so are known
- Trans-Neptunian Objects (TNO) – basically the stuff beyond Neptune, which now includes Pluto. With more discoveries some trends in their distribution are noted:
  - Kuiper Belt Objects – beyond Neptune, about 1150 known, sort of the main group.
  - Plutinos – found in a 3:2 resonance orbit with Neptune – 20% of TNO, around 39 AU from the Sun.
  - Twotinos – 2:1 resonance with Neptune, rarer, around 48 AU away

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- Scattered Disk Objects (SDO) – this would also include some Centaurs, and those on the outer edge of KB, found at higher inclination. This group includes Eris, the largest TNO.
- Oort Cloud – from beyond the location of the TNOs, out to around 50,000 AU away, there should be theoretically millions of objects. So far only about 30 objects have been found further than 100 AU out.

The various types of asteroids listed below is ordered primarily in distance out from the Sun. But the individual classifications are based upon the spectral features.

**E-type** – These are enstatite, forsterite rich, and have higher albedo (>0.3). They tend to be found on the inner edge of the asteroid belt and may be the source for enstatite achondrites meteorites.

**S-type** – silicaceous (stony), comprise about 17% of all asteroids, so it is a good fraction of the entire asteroid belt (2nd most common). They have a moderate albedo (between 0.1 and 0.2), and are comprised of metal, olivine, pyroxene. They may be the source of pallasites meteorites.

**Q-type** – sort of a rare type, with a spectra that shows olivine, pyroxene, metal, similar to what is seen in chondrite meteorites (H, L, LL). In general this might be thought of as being between a S, V type asteroid. They have a relatively high albedo.

**M-type** – composed of Ni-Fe, either in a pure metal or mixed with stone. Moderate albedo (0.1 - 0.18). These make up the third largest group and are likely the source of the iron meteorites.

*Taxonomy (classification) of Asteroids.*

What are these things like? It isn’t sufficient to just describe or classify them based upon their motion or location, but there should be a way of classifying them based on their observed chemical makeup and their likely histories. We’re able to do this mainly through spectrophotometry, which is sort of a reflection spectra. Analysis of the spectral features (molecules, absorption features) and the colors/albedos of the objects tell us what they are likely made of and what their relations to meteorites are. Most work in this area is done at IR wavelengths since you can see ices and molecules better at those wavelengths.
V-type – for Vesta. These are similar to S-types, but have more pyroxene as well as feldspar, like basaltic achondrite meteorites. Has a moderate to high albedo.

R-type – spectra shows olivine, pyroxene, possibly plagioclase. This type is somewhere between a V and A-type spectrally. Relatively high albedo and possibly a source for achondrite meteorites.

A-type – olivine features in spectrum, albedo of about 0.25 (high). Possibly the source for achondrites, pallasites meteorites.

C-type – Most common of all asteroids (75%) generally found beyond 2.7 AU, and appear to be most like the CI or CM meteorites. Very low albedos between 0.03 - 0.1, with water content in minerals (hydrated minerals), a bit reddish, containing OH silicates, carbon, organics.

B-type – a more bluish spectrum, not as reddish as the C-types, low albedo, contains OH silicates, carbon, organics. Could be the source for the altered CI, or CM meteorites.

F-type – similar to B-types, but lacks a water absorption feature. Very low albedo, with OH silicates, carbon, organics. Like the B-type could be the source for altered CI, CM meteorites.

G-type – like C-types, but with additional spectral features, possibly of phyllosilicate minerals like clays or mica, also have OH silicates, carbon, organics, very low albedo. And as the others, a possible source for the altered CI, CM meteorites.

T-type – A bit of a mystery. These have a dark, featureless spectra. They are thought to be anhydrous (no water), similar to P, D types or an altered C-type. Very low albedo, with OH, silicates, carbon, organics. Possibly the source for very altered CI, CM meteorites.

P-type – very low albedo (.07 or less). Possible composed of organic rich silicates, carbon, anhydrous silicates, water-ice interiors possible, reddish color. May be a source of dry, C-like meteorites.

D-type – very low albedo, organic rich silicates, carbon, anhydrous silicates, water-ice interiors possible, most Trojan Asteroids are this type. There may have been the detection of water on the surface of some of these objects. Very reddish color, source of dry C-like meteorites

Other classifications (taxonomy) are possible, though most are similar, and generally a subset for the S, C, and M groups, the anything outside of these groups is a pretty small part of the whole asteroid belt.

In general the types of asteroids can be ordered in terms of their characteristics in their distance from the Sun, which is roughly:

E, S, Q, M, V, R, A, C (includes B, F, G), T, P, D

Inner belt -----------------------------outer belt---------and beyond

Rocky/metally -----------------------------carbony/icy (organics/redder)
Asteroids?---------------------------------comets?
High albedo---------------------------------low albedo

Comet cores tend to be rather reddish spectra wise, so they would have a similar appearance to that of the outer asteroids, as well as the Trojans and Centaurs. The coloring is deceptive – a little bit of carbon goes a long way to alter the appearance of an object. Even though they do not have clean ice in them, objects that are C and later may still be mostly composed of ice with just enough organics/carbon to make them appear dark. In fact, the unusual object Sedna is as red as Mars!

Based on the taxonomy, it is possible to see a compositional history of these objects. There is a change in composition at around 2.5-2.7 AU where the composition goes from rock/metal to carbon (soot) covered objects. And it isn’t just carbon that is on their surfaces, but carbon-rich compounds which start to dominate the mix. There is of course still rock/metal (silicates, iron, nickel), but these are not as plentiful as the carbon-rich stuff at this distance from the Sun.

Once you get to 3-4 AU, ice starts to be added to the mix, and the ice will become a more dominate constituent at even greater distances. Even though ice is dominant, these objects are not bright and shiny. The small amount of carbon in them will make them dirty, dirty ice!

How did all of this stuff get to where it’s at? Some of this was sort of covered previously – the material may have formed at certain distances from the Sun, but things have moved around due to various perturbations.

In the inner solar system most asteroids would have been picked up (impacted/pulled in) by the terrestrial planets, and the Earth was the one that cleared a lot of them out, basically gravitationally throwing them to the outer solar system.

Jupiter and the other big guys would have thrown many of the icy objects in their neighborhood out to the deep freeze of the Kuiper Belt or the Oort cloud. If that hadn’t happened, the vast majority of the icy objects in the solar system would have melted long ago and all you’d have left are carbon rich objects. Actually we do see some of those that have been left behind as carbon rich objects in the outer solar system.

The position of objects in the asteroid belt is pretty much defined by Jupiter, and this is seen in the Kirkwood gaps. These gravitational gaps are at resonance locations in sync with Jupiter’s orbit.

The Trojans would have been those outer solar system objects that fell into the L4, L5 locations, but where did they come from? Were they formed at that location from the Sun or were they placed there from another location due to perturbations? This is hard to tell. Their colors are not as red as Centaurs and KBO, but they get more sunlight than those objects, so that doesn’t answer it (they could be faded Centaurs, or just originally inner solar system objects).
Detailed Studies

Enough about their orbital properties of these about, but what are these things really like? Generally we haven’t had too many up close opportunities to see comets and asteroids, but there have been a few exceptions.

Up close observations of comets has been through some spacecraft that studied them –
- Halleys Comet observed by Giotto and several other spacecraft (1986)
- Tempel observed/damaged by Deep Impact Spacecraft (2005), and later observed by Stardust (2011)
- Wild 2 observed by Stardust Spacecraft (2004)
- Hartley 2 observed by Deep Impact/EPOXI (2010)
The Giotto mission was the first mission to go inside of the coma of a comet to reveal the core, while Deep Impact involved a spacecraft dropping a capsule on the comet to produce an explosion and providing us a chance to see what was “under” the ice. Stardust was a collection mission with the spacecraft flying through the tail of a comet to pick up the particles that fly off. These could then be compared to dust that is picked up in the upper atmosphere of the Earth. The Deep Impact spacecraft was later renamed EPOXI since its observation of Hartley 2 was different in intent than the mission to Tempel. Most of these missions involve an array of cameras to measure composition of material and to gain a better understanding of the composition of comets.

Detailed observations of asteroids have involved several fly-by missions as well as specific missions that orbited the various asteroids –
- Gaspra, Ida – fly-by of the Galileo Spacecraft on its way to Jupiter
- Mathilde, Eros – NEAR/Shoemaker spacecraft which orbited Eros for a year
- Vesta – Dawn spacecraft orbited from July 2011 to September 2012
In addition to the space missions, asteroids have been studied from the Earth using either very high quality telescope imagery (usually only possible for largest asteroids), or radar imagery of asteroids flying by the Earth. Over 300 asteroids have been observed via radar imagery. Some of the fly-by asteroids include Toutatis, Geographos, Castalia, and Kleopatra, while both Vesta and Ceres are large enough to be imaged from the Earth with telescopes like the Hubble space telescope or the Keck telescopes.

Based on all of these spacecraft and the analysis of meteoritic material we have a better understanding of both comets and asteroids. We’ll first look at what we’ve learned about comets. Are they icy dirtballs or dirty iceballs? It seems that they are more like the latter – mostly made of ice with a bit of dirt. And of course ice comes in many forms such as NH3, CH4, CO2, as well as H2O ice, with water making up 50-80% of the mass. Comet cores are typically a few km in size, and recent observations of comet cores show them to be rather cratered – though the craters are shallow and smooth. Comets will flare up as they get closer to the Sun, though some can flare up at the distance of Jupiter (or more). Some objects have been observed to flare up at up to 20 AU.

Exactly what are these “flare ups”? This is basically the evaporation of material on the surface in large amounts, at least large enough to be observed. Flare ups can be rather violent, and it is
possible to see “jets” of material streaming off of the surface, possibly from fissures in the comet core. Very strong jets can alter the motion of the comets. The *EPOXI* mission observed a great deal of CO$_2$ vapor in its jets, and it seems to be the case that the majority of the water in comets may only be below the surface. In fact, the surfaces of some comets appear to be rather “dry”, such that any icy material on the surface is quickly removed.

Usually at around 3 AU the amount of evaporated material gets pretty large, and a coma will develop around the comet core. This is a hydrogen rich cloud of material around the core which is several million km in size in some cases. Generally the coma is largest at about a distance of 2 AU.

Along with the coma, the tails of the comet start to develop in the inner solar system. There are two tails, the Type I tail (also called the gas or ion tail) and the Type II tail (the dust tail). The Type I tail is strongly affected by the solar wind, and the solar winds can also accelerate the motion of material away from the comet. The Type II tail is most affected by radiation pressure from the Sun, which isn’t as strong, so it doesn’t get pushed back as strongly. Generally speaking the Type I tail points away from the Sun while the Type II tail tends to trail behind the comet.

Astronomers have observed more than 30 different gases from comets (in the coma and tails). The gases are likely from the ices, and are in various combinations of C, H, O, N and many of these are ionized. We also detect a fair amount of sulfur, but we’re not quite sure where that is from. Comets are also rich in dust, which contains CHON particles (stuff made up of CHON) and that makes the dust different from Earth dust which has more Si, and Fe in it. Comets that get really close to the Sun show more material coming from them, elements such as K, Ca, Fe, Cu, Ni, V, Mn, Co, Cr, Si, Mg, Al, Ti, Na, have been observed but only at the highest temperatures.

So comets are basically ice (water) with a smattering of CHON, sooty carbon rich particles and a smattering of other elements. This makes the comet core very dark, with an albedo of only 2-5%.

And as a comet continues to orbit around the sun, the ice/carbon ratio decreases since the ice is lost more readily than the carbon. The sizes of comet objects (and potential comet sources like those in the KBO and the Oort cloud) is inversely proportional to the number of such objects. Very few cometary cores are larger than 500 km, at most they are only a few km in size. It is estimated that there are 35,000 KBO between 100-300 km in size while there are $10^8$-$10^9$ objects about 1 km in size.

Comets are generally thought to be rather fragile since they are prone to break up, even if they are not significantly close to the Sun. This has been observed in the past and evidence for previous breakups is seen in the strings of craters observed on the surfaces of many worlds.

And of course meteor showers are associated with comets. The material blown off of comets is in orbit about the Sun as well since it is from the comet and has some of the comet’s orbital features, so it is influenced by all of the forces that change the motion of objects. Over time the
material gets spread out in the orbit, and the path of the material gets widened as well – and diluted. Most meteor showers don’t have a known comet source. Generally meteor shower material doesn’t make it to the surface of the ground, since the material is so small to begin with.

Our studies of asteroids show that these are rather similar to what you would expect based upon the characteristics of meteorites, but of course there are always some complications. We find asteroids to be generally rocky, with the majority comprised of carbon rich material (C-types dominate). Typically they have a pretty low albedo value. The density varies with type, such that a C-type has a density close to 1200 kg/m³, while the M-types have densities closer to 4000 kg/m³. These values are a bit lower than meteorites that we think come from asteroids. Since asteroid densities are pretty low, there are likely good amounts of water/volatiles in them as well as the rocks and minerals, and naturally lots of this is lost when the object becomes a meteorite. Or it is possible that asteroids are just very porous objects.

Observations of asteroids show that most have rotation rates that are rather slow, especially those with larger sizes, typically a few hours at most. This allows them to have a “soil”, more properly a “regolith” of material on their surface. This would be dust and material that accumulates over time. This regolith could be a few cm thick, or more. It generally appears to be sort of a fluffy dust. There may be compacted layers under the lighter, fluffy material above it. Observations of the asteroid Eros show boulder sized objects on the surface, which was unexpected. We thought that if an asteroid were impacted so that boulders and rocks were produced, these objects would fly off and not fall back onto the asteroid (since it has a low surface gravity), but apparently some material has stayed with the asteroid. Also the slow rotation helps - if asteroids spun around too fast, they’d lose their surface material.

4.5 Killer Impacts!

Most impacts by meteoritic material is not violent or damaging, however some impacts have been lethal in the past, either directly or indirectly – just ask the dinosaurs. But that is something a bit too far in the past. Let’s look are more recent impacts that were “noticeable”.

We’ll first look at an impact that didn’t occur on the earth, but on another planet. Comet Shoemaker Levy 9 (also known as D/1993 F2) was discovered March 24, 1993. At the time it was noted to be just a relatively “flat” looking objects out by Jupiter. An early nickname was “the string of pearls” since the comet had fragmented into multiple pieces. Once more observations were made, it was determined that the comet was on a collision course with Jupiter, and would hit it in July 1994. It is generally thought that this object had just passed a little too close to Jupiter in 1992 at which time it might have been ripped apart, but more importantly, its orbit was altered just enough to put it on the collision course. The close encounter had brought it within 1.3 x radius of Jupiter which is well within the Roche Limit for the planet. It is possible that the comet may have been around since the 1920s, with its orbit being altered by Jupiter slowly over time.

Careful observations of the comet revealed a total of 21 individual pieces initially which were labeled A-W (but no I or O to avoid confusion). Over the next few months some of these objects disappeared over time, while others broke into two or three pieces. Since SL9 was too far from
the Sun to develop a significant coma or tail, the fuzziness around it was thought to be due to dust.

And then the first chunk was set to hit Jupiter on the night of July 16, 1994. And it did not disappoint. You have to remember, these pieces are moving at a good pace, with the velocity at impact on the order of 60 km/s. The resulting fireball temperature was close to 10,000 K. That’s hotter than the surface of the Sun! The only problem with observing the impacts was that they occurred on the “edge” of Jupiter as we see the planet, sort of behind it actually, so we didn’t see anything directly. Infrared images did reveal the large fireball caused by the impact on the atmosphere as well as strong heating in the clouds of Jupiter since those explosions were large in extent.

Impact features showed the presence of water vapor, sulfur vapor, and sulfur compounds. This indicates a composition that is rather chondritic, like a cometary object. Also the markings were rather dark on the surface of Jupiter, indicating a carbon rich material. The eruptions of material from the fireballs of Jupiter don’t really help us figure out what the object was like originally, since Jupiter has a composition that can mask the material from the cometary source. It is possible that this object wasn’t a comet, but could have been more asteroid-like. Unfortunately by July 22, the party was over and the object no longer existed.

Another major impact event in human history was the 1908 event in Tunguska Russia. At 7:17 AM on June 30, a large object exploded in the atmosphere, about 6 km up. Even though it wasn’t a “hit” on the surface of the Earth, the effects were easy to measure. Observations around the world and interviews of the few people that lived in that region provided some rather amazing observations –

- While the Richter scale had not yet been developed, there were measurements from various seismic stations that were the equivalent of a 5.0 magnitude earthquake.
- Dust in the atmosphere was increased and this caused a great deal of glow in the east as seen from Europe. People in London could read a newspaper at midnight due to this glow in the sky. Measurements indicated that this dust hung around for several months impacting the atmospheric transparency.
- Barometers around the world measured abrupt fluctuations in air pressure.
- At a distance of 500 km away, there were reports of loud noises and a fiery cloud on the horizon
- At a distance of 400 km away people saw a ball of fire and heard deafening crashes like thunder and later loud bangs like gunshots
- Only 60 km away you have the following eyewitness accounts:
- I was sitting on the porch of the house at the trading station, looking north. Suddenly in the north…the sky was split in two, and high above the forest the whole northern part of the sky appeared covered with fire. I felt a great heat, as if my shirt had caught fire…. At that moment there was a bang in the sky, and a mighty crash…I was thrown 20 feet from the porch and lost consciousness for a moment….The crash was followed by a noise like stones falling from the sky, or guns firing. The earth trembled….At the moment when the sky opened, a hot wind, as if from a cannon, blew past the huts from the north. It damaged the
onion plants. Later we found that many panes in the windows had been blown out and the iron hasp in the barn door had been broken

- I saw the sky in the north open to the ground and fires pour out. The fire was brighter than the sun. We were terrified, but the sky closed again and immediately afterward, bangs like gunshots were heard. We thought stones were falling….I ran with my head down and covered, because I was afraid stones [might] fall on it.

- Only 30 km from the impact the following details were conveyed:
  - Early in the morning when everyone was asleep in the tent, it was blown up in the air along with its occupants. Some lost consciousness. When they regained consciousness, they heard a great deal of noise and saw the forest burning around them, most of it devastated. The ground shook and incredibly prolonged roaring was heard. Everything round about was shrouded in smoke and fog from burning, falling trees. Eventually the noise died away and the wind dropped, but the forest went on burning. Many reindeer rushed away and were lost.
  - One older man at this distance was reportedly blown about 40 feet into a tree, suffered a compound fracture of the arm and died soon after. Hundreds of the reindeer were killed. Many campsites and storage huts were destroyed.

Since the location was so remote, it wasn’t until 1927 that a scientific expedition was able to examine the site. No crater was found at the location, but there was a large region with trees knocked over. However at the center of this the trees were still standing, though they had their branches and bark stripped off. Later expeditions found microscopic silicate and magnetite spheres, which also had relatively high amounts of nickel compared to iron. This evidence points to an extraterrestrial origin. The energy associated with the event is around 20 megatons of TNT. So was it a comet or an asteroid? The object did not produce a crater, which indicates a comet source. Some have suggested that the object may have been part of the Beta Taurid meteor shower, which originated from the Comet Encke. Other studies have shown compositions of the material that was left behind is more like that found in stony meteorites rather than cometary material.

Russia must be an impact magnet, since another major impact occurred on February 15, 2013. This impact was at around 9:20 AM local time in the area known as Chelyabinsk (south central Russia, near Kazakhstan). The object’s path was well observed due to the common use of security, traffic and dashboard cameras. The object was traveling at an estimated speed of 18 km/s and exploded about 20 km above the ground. The shock wave from this explosion caused most of the damage, particularly in the form of windows blown out. Approximately 1500 people were injured mainly due to broken glass and material hitting them. The energy of the explosion was around 500 kilotons of TNT, which makes it more powerful than the atomic bombs of Hiroshima and Nagasaki, but less powerful than Tunguska.

Analysis of video images of the meteor’s path indicates that the object likely belonged to the Apollo asteroid family. The estimated size of the object was around 15 meters, a size below most of our detection abilities. Meteorites are being collected in the region, and appear to be a type of ordinary chondrite, perhaps an L or LL type, though that has yet to be determined.