Meteorites and the Early Solar System

Lecture 6

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Every day we receive 50 tons of interplanetary material
Types of Meteorites

- **CHONDrites.** 82% of meteorite falls are chondrites.
- **ACHONDrites.** 8% of meteorite falls are achondrites.
- **STONY-IRONS.** 5% of meteorite falls are stony-irons.
- **IRONS.** 5% of meteorite falls are irons.

Observed falls are likely to represent true ratios, whereas finds are heavily weighted towards iron meteorites.

It is unclear if the ratio of meteorite types falling changes with time.
Ordinary chondrites are the most common type of stone meteorite. All chondrites contain chondrules, small spherical inclusions. Ordinary chondrites are further grouped by H, L and LL classifications, indicating iron content, and by the numbers 3–7, indicating the amount of change or metamorphism in the chondrules.

**H chondrites** have the highest iron content – 27 percent total iron by weight. They are commonly referred to as olivine-bronzite chondrites. **L chondrites** have a lower iron content, roughly 23 percent by weight and are referred to as olivine-hypersthene chondrites. **LL chondrites** represent "low iron" and "low metal" content. Sometimes referred to as amphoterites, they contain only 20 percent total iron.

The numbers following the H, L and LL classifications are petrologic grades indicating the degree of chondrule alteration by heating. Well defined, unaltered chondrules have a petrologic grade of 3 or 4. A higher number of 5 or 6 indicates an increased level of metamorphism making the chondrules less distinct.
Carbonaceous Chondrites

Carbonaceous (C) chondrites are some of the most complex of all meteorites. They are rare, primitive and contain organic compounds. Most importantly they contain water-bearing minerals which is evidence of water moving slowly through their interiors not long after formation.

C chondrites are further divided according to chemical and mineralogical differences into the sub-classes CI, CM, CV, CO, CK and CR. These sub-classes are named for the type specimen of each group, Ivuna, Mighei, Vigarano, Ornans, Karoonda and Renazzo respectively.

Like the ordinary chondrites, C chondrites also have petrologic grade designations. In addition to grades 3 to 6, indicating increasing heat metamorphism of chondrules, grades 2 and 1 indicate increasing metamorphism of the meteorite by water. Carbonaceous chondrites are the only meteorites known with petrologic grades 1 and 2.

Two carbonaceous chondrites, Allende and Murchison, are of particular interest to scientists and, curiously, both fell in 1969, but on opposite sides of the world.
Achondrites are very similar in appearance to terrestrial igneous rocks. As such they are very difficult to find unless the fall has been witnessed. There are over a dozen different sub-classifications of achondrites, but many of them have only one or two specimens associated with them. Only the more numerous types have been included in this discussion.

Because achondrites are igneous in nature they are believed to have formed on differentiated bodies in the solar system. Differentiated bodies are large enough to have been completely molten at one time allowing heavier elements to sink towards the center of the layered mass. This results in a body, like the Earth, where there are chemically distinct core, mantle and crust areas. This complete melting also removes all evidence of chondrules, hence achondrite, meaning without chondrules.

Achondrites

The HED group of achondrites comprises the related types Howardites, Eucrites and Diogenites. Very careful analysis of the spectra of these meteorites and comparison of them with the spectra of asteroids using the Hubble Space Telescope provides compelling evidence that this group of meteorites comes from asteroid 4 Vesta.

Eucrites are volcanic pyroxene and feldspar and correspond well spectrally to the lava flows on the crust of 4 Vesta. Diogenites are plutonic pyroxene in nature and match areas of 4 Vesta that appear to be large craters exposing the interior mantle of the asteroid. Howardites are a breccia of Eucrites and Diogenites implying that fragments of these materials have been fused together by subsequent impacts.
Stony-Iron Meteorites - Mesosiderites

Mesosiderites are among the strangest of all meteorites. They are a breccia of an approximately equal mixture of silicates and metal that is indicative of multiple and repeated impacts.

The silicate material is somewhat similar to the eucrite material found in howardites, but has chemical differences that suggest additional mixing with other types of rock. The metals found in mesosiderites are very uniform, in contrast to the range of metal compositions found in iron meteorites. This implies that the metal in mesosiderites has a different origin than the irons.

Mesosiderites are considered the "dumping ground" of meteorites as they appear to be a surface regolith that has been stirred up and fused by repeated impacts. Some mesos have recrystallized indicating they may have been deeply buried and somehow reheated at one point in their history. The mesosiderite Vaca Muerta from Chile is an example of the type.
Stony-Iron Meteorites - Pallasites

Pallasites contain crystals of olivine, the semi-precious stone peridot, contained within a matrix of nickel-iron. The color of the olivine crystals can vary from a deep amber to light green depending on the particular meteorite being viewed. In thin slices of pallasites, the crystals are translucent to light.

Pallasites are very scarce and believed to have formed on differentiated bodies in the transition area between the metal-rich core and the olivine-rich mantle where the olivine could cool slowly enough to form relatively large crystals.
Iron Meteorites

Two classifications are in use.

The older **Structural classification** is based on the relative abundance of nickel to iron, which can be assessed from the appearance of polished cross-sections that have been etched with acid. The categories are:

- Hexahedrites (low nickel)
- Octahedrites (average to high nickel), most common
- Ataxites (very high nickel), rare

The Octahedrites can be further divided up on the basis of the properties of their Widmanstaetten patterns.

A newer **Chemical classification** based on the proportions of trace elements separates the iron meteorites into classes corresponding to distinct asteroid parent bodies.

The majority of iron meteorites originate from M-type asteroids, which are fragments of the cores of larger ancient asteroids that have been shattered by impacts.

Chemical and isotope analysis indicates that at least about 50 distinct parent bodies were involved. This implies that there were once at least this many large, differentiated, asteroids in the asteroid belt - many more than today.
On April 10 in 1972, a huge body, estimated to be the size of a house, entered the Earth's atmosphere above western USA with a speed of 15 km per second. By amazing luck it came in at such a low angle that it flew as a brilliant fireball across Utah, Idaho and Montana, without ever getting closer to the ground than perhaps 50 km. It was seen in plain daylight by many thousands of people and photographed and filmed. Finally it left the Earth's atmosphere somewhere over Canada. It is now circling the Sun as a charred and blackened body. But some day in the future it will be back.
The Connection between Asteroids and Meteorites

Asteroid 2008 TC3 at 150,000 km from Earth
06-10-2008, from 21.10 (right) to 21.24 (left) TU
Newton 350mm F/5, CCD ST10-XME, no filters
Exposure: 15x10s, 60s between frames
On 6 October 2008, a small asteroid was discovered with a flat reflectance spectrum in the 554–995 nm wavelength range, and designated 2008 TC$_3$. It subsequently hit the Earth. Because it exploded at 37 km altitude, no macroscopic fragments were expected to survive.

A dedicated search along the approach trajectory recovered 47 meteorites, fragments of a single body named Almahata Sitta, with a total mass of 3.95 kg.

Analysis of one of these meteorites shows it to be an achondrite, a polymict ureilite, anomalous in its class: ultra-fine-grained and porous, with large carbonaceous grains.

The combined asteroid and meteorite reflectance spectra identify the asteroid as F class, now firmly linked to dark carbon-rich anomalous ureilites, a material so fragile it was not previously represented in meteorite collections.
Map of the Nubian Desert of northern Sudan with the ground-projected approach path of the asteroid and the location of the recovered meteorites.
Origin of Meteors

Radiants of 39,208 meteors observed by SonotaCo Network in 2007-2008
An equilibrium diagram for a solar nebula at 10-3 bar showing mineral stability above 900 K. At 900 K, half the atoms in a CI chondrite are condensed; S and other volatile elements are in the gas. In a cooling nebula, only three minerals condense entirely from the gas: corundum, forsterite, and Fe,Ni metal - the remainder form by reaction between solids and gas.
**Chondrules and Ca-Al-rich Inclusions**

CHONDRULES are the major constituents of most chondrites. They are roughly millimeter-sized particles that were wholly or partly molten in the solar nebula and crystallized in minutes to hours between ~1800 and ~1300 K prior to accretion into the chondrite matrix - the fine-grained silicate material that coats chondrules and fills the interstices between them. Chondrites were a major component of the material that accreted into the terrestrial planets.

CALCIUM-ALUMINUM-RICH INCLUSIONS (CAIs) are the other major constituent of chondrites. They are composed of refractory (elements that condense at high temperatures). Chondrules and CAIs are closely related, although CAIs formed at higher nebular temperatures.

Both chondrules and CAIs have fine-grained rims that were acquired after these objects cooled, probably as the chondritic components accreted together.
Formation of Chondrules

It has for many years been a mystery how chondrules form. It is now believed that shock waves moving through the early solar nebula have melted dustballs into molten droplets, which then rapidly cooled to become chondrules.

There are many suggestions for how shock waves could be generated in the early solar nebula. One hypothesis is that a companion star, later lost in a dense cluster, ploughed through the early solar nebula.

Many chondrules have been melted more than once, as evidenced by chondrules inside chondrules.
Ages of Chondrules and CAIs

After considerable efforts to identify and date pristine chondrules and CAIs that have not had their isotopic systems reset by asteroidal processing, a consistent chronology for the formation of chondrules and CAIs has finally been achieved.

The most precise absolute ages of chondrules and CAIs come from studies of radioactive decay. CAIs are now dated to 4567.2+-0.6 Myr and chondrules are dated to 4566.7+-1.0 Myr for CV chondrites, 4564.7+-0.7 Myr for CR chondrites, and 4562.7+-0.5 Myr for CB chondrites. Thus they all formed within a period of 4.5 Myr, consistent with the lifetime of disks around T Tauri stars.
The Sun’s Birth Environment?
It is likely that the Sun was born in a cluster

• The meteoritic record indicates that the early solar nebula was enriched by short-lived radioactive nuclei. It is commonly believed that this is the result of a supernova that exploded within about 2 pc. For a normal Initial Mass Function, a cluster of about 2000 stars or more is required for at least a 50% probability that a 25 Msun star is formed in the cluster.

• The orbits of Kuiper Belt objects can be affected if a cluster member approaches to within 100 - 200 AU, pumping up the velocity dispersion of the more distant Kuiper Belt objects and leading to a steep increase in their eccentricities and inclinations. A close approach by another star is also consistent with the observed sharp edge of the Kuiper Belt.

• The solar obliquity (angle between the Sun’s rotational axis and the angular momentum vector of the Solar System) is 7 degrees. This may be a memory of a close passage of a cluster member, or of the Sun even being a member of a multiple system, that later disintegrated.
We know that these short-lived isotopes decayed within chondrites, because we find excesses of the daughter isotopes that are correlated with the abundances of a stable isotope of the parent element. For example, 26Mg/24Mg ratios in diverse minerals in CAIs are correlated with 27Al/24Mg ratios, showing that the decay of 26Al to 26Mg happened in situ.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-life (Myr)</th>
<th>Daughter</th>
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<tbody>
<tr>
<td>41Ca</td>
<td>0.10</td>
<td>41K</td>
</tr>
<tr>
<td>26Al</td>
<td>0.74</td>
<td>26Mg</td>
</tr>
<tr>
<td>10Be</td>
<td>1.5</td>
<td>10B</td>
</tr>
<tr>
<td>60Fe</td>
<td>1.5</td>
<td>60Ni</td>
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<tr>
<td>53Mn</td>
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<td>53Cr</td>
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<tr>
<td>107Pd</td>
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<td>107Ag</td>
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<tr>
<td>182Hf</td>
<td>9</td>
<td>182W</td>
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(1) Radiation from a massive star drives an ionization front into surrounding molecular gas.

(2) The ionization front (plus winds and previous SNe) drive a shock, triggering collapse of molecular cores.

(3) ~100,000 years after triggered collapse, the ionization front overruns the core, forming an EGG.

(4) EGGs evaporate in ~10,000 years, exposing the disk. The evaporating disk is a proplyd.

(5) In ~10,000 years, disks erode to ~50 AU. Disk evaporation ends, leaving a protostar and bare protoplanetary disk.

(6) The massive star goes supernova, injecting newly synthesized elements into surrounding disks.
This process takes place now in M16
Star Formation in EGGs
(Evaporating Gaseous Globules)