Meteorite on Mars being examined by the Mars Exploration Rover
Topics

What are meteorites and what do they tell us about geological processes on planetary bodies?

Extinct isotopes, core formation, and the earliest days of the Solar System

Different types of meteorites
Solar System Formation: The Nebular Hypothesis

The rotating disk surrounding a protostar consists of:

- gases (primarily H and He)
- heavier elements (Si, Fe, C, Ni, etc....)
- ices (water, methane, ammonia; covers dust particles)

Some regions become more concentrated as materials collide and stick together. This forms **planetesimals**.

Planetesimals eventually become large enough to exert gravitational pull on each other. They begin to collide and grow rapidly in size. They can then become **protoplanets**.

This process is often referred to as **planetary accretion**.
The Solar System ‘Frost Line’

The interior part of the accretion disk is hot and hydrogen remains vaporized, but rock and metal can condense to form terrestrial planets.

In contrast, the outer portion is cooler and ices can begin to form, leading to the rock/ice cores of gas giants and to the formation of icy moons.
Our Solar System is 4.56 Gyr (Gyr = billion years old).

This has been determined by age-dating meteorites, which we believe are representative of the earliest period in the Solar System.

Some meteorites are very primitive, meaning they formed very early in the Solar System and contain material that tells us a lot about the conditions and chemistry of interstellar space.

A specific group of meteorites, known as the carbonaceous chondrites, have a chemical composition that is nearly identical to the photosphere of the Sun.
Meteoroids are pieces of extraterrestrial objects traveling through space, and they can be from asteroids, planets (e.g., Mars), or the Moon.

Meteorites are pieces of meteoroids that have survived transport through the atmosphere and landed on the surface (they are called meteorites once they reach the surface).

Meteors that you observe in the sky can be caused by material as small as a grain of sand or by boulder-sized objects.

Very small meteorites are called micrometeorites.

Meteorites can be classified as ‘finds’ or ‘falls’.

- ‘finds’ are ones for which the entry to Earth was not observed, but the meteorite was later found and identified as extraterrestrial

- ‘falls’ are ones for which the entry was actually witnessed; quite rare but very important for determining statistics
During entry, frictional heating melts the outer surface, forming a **fusion crust**.

Up to 50% of the meteorite can be burned away, but the interior of the meteorite remains cold and unchanged.
The Sky is Falling!
There are a number of excellent meteorite collections throughout the world.

Some samples have been collected by researchers, some by the general public, and many by professional meteorite hunters.
Annual expeditions to Antarctica has dramatically increased our meteorite collections: glaciers provide a natural concentration mechanism.
Finding Meteorites: Antarctica

Annual expeditions to Antarctica has dramatically increased our meteorite collections: **glaciers provide a natural concentration mechanism.**

Ice flow in glaciers acts to bring meteorites back up to the surface and concentrates them in the ablation zone (area of a glacier where ice is sublimating).

Also, dark objects like meteorites are relatively easy to see on white snow/ice.
Breakdown of Where Meteorites are Found

Where Are Meteorites Found?

- Antarctica: 69.8%
- North Africa: 14.3%
- Oman: 6.0%
- North America: 4.4%
- Everywhere else: 5.4%

World: N = 39545

Data from the Meteoritical Bulletin Database, November 9, 2010
Asteroids: Primary Source of Meteorites

Most meteorites come from asteroids, but some are known to have come from the Moon and Mars.

Meteorites are very important because they provide a direct way for us to characterize the rock types and chemical composition of objects in the Solar System.

Some meteorites also contain material that is older than our Solar System (presolar grains); this material tells us of the chemistry of other stars and molecular clouds.
Meteorites and the Early Solar System

The chemistry of materials that we find here (today) can tell us about processes that occurred here (in the past).
Important Minerals on Terrestrial Planets & Asteroids

**Olivine**

$(\text{Mg,Fe})_2\text{SiO}_4$

These minerals are relatively dark and make up ‘mafic’ rocks, such as basalt.

**Pyroxene**

$(\text{Mg,Fe,Ca})_2\text{Si}_2\text{O}_6$

**Feldspars**

**Plagioclase**

- **Albite**
  \(\text{NaAlSi}_3\text{O}_8\)

- **Anorthite**
  \(\text{CaAl}_2\text{Si}_2\text{O}_8\)

**K-Feldspar**

\(\text{KAlSi}_3\text{O}_8\)

These minerals are relatively light and make up ‘felsic’ rocks, such as granite.
We can cut rocks into very thin slices, polish them, and see how they reflect or transmit light. This can be used to identify minerals.

**Olivine**
(Mg,Fe)$_2$SiO$_4$

**Pyroxene**
(Mg,Fe,Ca)$_2$Si$_2$O$_6$

<table>
<thead>
<tr>
<th>Feldspars</th>
<th>Plagioclase</th>
<th>Albite</th>
<th>Anorthite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NaAlSi$_3$O$_8$</td>
<td></td>
<td>CaAl$_2$Si$_2$O$_8$</td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>KAISi$_3$O$_8$</td>
<td></td>
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</tr>
</tbody>
</table>
In the solar nebula (molecular cloud), grains of dust begin to form and can stick together when they bump into each other (kind of like dust bunnies).

At some point, somehow, clumps of the early material were heated, melted, and then quickly cooled. Their round shape indicates that they were formed by melt droplets in low gravity.

The clumps start small, but they grow and continue to get bigger and bigger, forming planetesimals and ultimately planets.

Therefore, these tiny blobs of ‘rock’ are really the seeds of planets. These small objects are called **chondrules**, and they are found in chondrite meteorites. They are typically made of the minerals olivine, pyroxene, and feldspar.
Figure 9. Porphyritic olivine chondrule (PO) with metal-sulfide-rich rim. PL on left, XPL on right.

Figure 10. Porphyritic olivine chondrule. PL on left, XPL on right.

http://www4.nau.edu/meteorite/Meteorite/Book-Chondrules.html
Figure 11. Porphyritic pyroxene (PP) chondrule with a few olivine grains (bright colors). PL on left, XPL on right.
Equilibrium diagram showing which minerals are stable between 900 and 1800 K in a nebula of solar composition at $10^{-3}$ bar (after Davis & Richter 2003). At 900 K, half the atoms (0.55) in a CI chondrite are in minerals; S and other volatile elements are in the gas. Minerals stable above 1400 K are found in refractory inclusions; minerals stable below 1400 K predominate in chondrules and matrix material. Only three minerals condense entirely from the gas on cooling—corundum ($\text{Al}_2\text{O}_3$), forsterite ($\text{Mg}_2\text{SiO}_4$), and Fe,Ni metal—the remainder form by reaction between solids and gas. Liquids are unstable unless the total pressure or the dust/gas ratio is increased 10–100×.
Our estimate of the age of the Solar System and planetary formation comes from meteorites, and this is done by measuring the chemistry of those meteorites.

A specific group of meteorites, known as the carbonaceous chondrites, have a chemical composition that is nearly identical to the photosphere of the Sun.

These meteorites also contain Calcium-Aluminum Inclusions (CAIs), and these CAIs are the oldest known material from our Solar System.

The CAIs are ~2 million years older than chondrules and give a **Solar System age of 4.567 Ma.**
letters to nature

Contemporaneous formation of chondrules and refractory inclusions in the early Solar System

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Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan

Chondrules and calcium-aluminium-rich inclusions (CAIs) are preserved materials from the early history of the Solar System, where they resulted from thermal processing of pre-existing solids during various flash heating episodes which lasted for several million years. CAIs are believed to have formed about two million years before the chondrules. Here we report the discovery of a chondrule fragment embedded in a CAI. The chondrule’s composition is poor in $^{16}$O, while the CAI has a $^{16}$O-poor melilite (Ca, Mg, Al-Silicate) core surrounded by a $^{16}$O-rich igneous mantle. These observations, when combined with the previously reported CAI-bearing chondrules, strongly suggest that the formation of chondrules and CAIs overlapped in time and space, and that there were large fluctuations in the oxygen isotopic compositions in the solar nebula probably synchronizing astrophysical pulses.

Figure 1 Back-scattered electron image of the chondrule-bearing CAI. The object, named A5, was found in a thin section (no. 56-4 from the National Institute of Polar Research, Tokyo) of the Y81020 CO3.0 chondrite. Horizontal and vertical scales are in mm. Scale bar also at top right. Locations of SIMS analyses are shown by numbers corresponding to those in Table 1. The circle size round each number shows the approximate analytical area of O isotopic composition by SIMS. The CAI consists of a large central polycrystalline melilite ($A'$ k10–13, Mel) clast in which individual melilite crystals are about 20 mm across. Fine perovskite grains (white spots) are scattered in and around the melilite. The melilite clast is enclosed by a porous mesostasis (Mes) composed of a fine-grained mix of Al-rich clinopyroxene and Al-rich glass. Also enclosed by the porous mesostasis is a pyroxene assemblage dominated by enstatite (En) with minor pigeonite (Pig) and augite (Aug). The augite is an overgrowth on the pigeonite. Troilite (Tr) is minor phase associated with the pyroxene assemblage. Troilite and Fe-Ni metal (white spots) are scattered in the mesostasis near the pyroxene assemblage. The right lower side of the CAI is broken surface where the pyroxene assemblage directly borders the matrix (Mx). Other abbreviations: Ol, olivine; Chond, chondrule; AOA, amoeboid olivine aggregate.

CAI & Chondrule Formation
Time scales of solid formation and disk evolution. The brief formation interval of 160,000 years for the CAI-forming event is similar to the median lifetimes of class 0 protostars of ~0.1 to 0.2 My inferred from astronomical observation of star-forming regions (37). Therefore, the thermal regime required for CAI condensation may only have existed during the earliest stages of disk evolution typified by high mass accretion rates ($\sim 10^{-5} \text{ M}_\odot \text{ year}^{-1}$) to the central star.
Presolar Grains (Stardust)

Chondrites also contain **presolar grains**.

These are pieces of stardust from the molecular cloud that formed *before* the formation of our Solar System, and they originate from other stars shedding their mass and from supernovae.

Presolar grains are typically made of very resistant materials: silicon carbide, graphite, and very tiny diamonds. Their chemistry shows that they could not have formed in our Solar System.

**Isotopes** are atoms of the *same element* that have different *mass* (such as carbon-12 and carbon-13); the ratios of these stable isotopes are more or less the same for our entire Solar System, yet the values for presolar grains are quite diverse.

If these grains were from the formation of our Solar System, then all of the red bars in the graph to the left would be collapsed onto the blue dashed line (value for our Sun).
Planetary Composition & Differentiation

How do we know the age of planetary objects? **Isotopic dating from radioactive elements.** (remember that isotopes are atoms of the same element that have a different mass)

But this doesn’t tell us when the core formed, so how do we know that?

<table>
<thead>
<tr>
<th>ISOTOPES</th>
<th>HALF-LIFE OF PARENT (YEARS)</th>
<th>EFFECTIVE DATING RANGE (YEARS)</th>
<th>MINERALS AND OTHER MATERIALS THAT CAN BE DATED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PARENT</strong></td>
<td><strong>DAUGHTER</strong></td>
<td><strong>(YEARS)</strong></td>
<td><strong>(YEARS)</strong></td>
</tr>
<tr>
<td>Uranium-238</td>
<td>Lead-206</td>
<td>4.5 billion</td>
<td>Zircon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 million-4.6 billion</td>
<td>Uraninite</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>Argon-40</td>
<td>1.3 billion</td>
<td>Muscovite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50,000 - 4.6 billion</td>
<td>Biotite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hornblende</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Whole volcanic rock</td>
</tr>
<tr>
<td>Rubidium-87</td>
<td>Strontium-87</td>
<td>47 billion</td>
<td>Muscovite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 million-4.6 billion</td>
<td>Biotite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potassium feldspar</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Whole metamorphic or igneous rock</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>Nitrogen-14</td>
<td>5730</td>
<td>Wood, charcoal, peat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 - 70,000</td>
<td>Bone and tissue</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Shell and other calcium carbonate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Groundwater, ocean water, and glacier ice containing dissolved</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>carbon dioxide</td>
</tr>
</tbody>
</table>
As planets undergo accretion, the heavy elements (Fe, Ni, S) will tend to sink to the center to form a metallic core. This is called planetary differentiation, and there are still many unanswered questions about the specifics of how this process occurred.

The lighter elements (Mg, Ca, Al, etc.) will remain outside the center to form the mantle. The outermost layer of the mantle is exposed to the atmosphere/space and will cool rapidly to form the initial crust.

But meteorites give us insight into this process!
Normal Isochron
Daughter/Stable D

Parent/Stable D

\[(D/D_S)_0\]

\(t_0\)

\(t_1\)

\[\text{slope} = \exp(\lambda t - 1)\]

Generalities

- Al-Mg
- Hf-W

(slides from Terik Daly)
Al-Mg System

- $^{26}\text{Al} \rightarrow ^{26}\text{Mg} + \beta^+ + \nu_e$

- Excess $^{26}\text{Mg}$ in CAIs, chondritic materials, achondrites (e.g., eucrites)

- $t_{1/2} = 0.72$ Myr (“gone” in 3.6 Myr)

- Used to date CAIs through planetesimal accretion

(slides from Terik Daly)
Generalities

- $^{26}\text{Mg}/^{24}\text{Mg}$
- $^{27}\text{Al}/^{24}\text{Mg}$
- $^{176}\text{Hf}/^{176}\text{W}$

Timeline

$t_0$ older than $t_A$

slope = $^{26}\text{Mg}^*/^{27}\text{Al} = (^{26}\text{Al}/^{27}\text{Al})_A$

(slides from Terik Daly)
Faure and Mensing (2005)

\[
\frac{\frac{26}{27}Al}{\frac{26}{27}Al}_{A} = e^{-\lambda t_{A}} \left( \frac{\frac{26}{27}Al}{\frac{26}{27}Al} \right)_{i}
\]

\[
\frac{\frac{26}{27}Al}{\frac{26}{27}Al}_{B} = e^{-\lambda t_{B}} \left( \frac{\frac{26}{27}Al}{\frac{26}{27}Al} \right)_{i}
\]

\[
\frac{\frac{26}{27}Al}{\frac{26}{27}Al}_{A} = e^{-\lambda t_{A}}
\]

\[
\frac{\frac{26}{27}Al}{\frac{26}{27}Al}_{B} = e^{-\lambda t_{B}}
\]

\[
\frac{\frac{26}{27}Al}{\frac{27}{24}Mg}_{A} = e^{\lambda \Delta t}
\]

\[
\frac{\frac{26}{27}Al}{\frac{27}{24}Mg}_{B} = e^{\lambda \Delta t}
\]

\[
\Delta t = \frac{1}{\lambda} \ln \frac{\left( \frac{\frac{26}{27}Al}{\frac{27}{24}Mg} \right)_{time A}}{\left( \frac{\frac{26}{27}Al}{\frac{27}{24}Mg} \right)_{time B}}
\]

(slides from Terik Daly)
\[ \text{Slope gives } \frac{^{26}\text{Al}}{^{27}\text{Al}}. \]

\[ \text{Intercept gives initial } \frac{^{26}\text{Mg}}{^{24}\text{Mg}} (\frac{^{26}\text{Al}}{^{24}\text{Mg}}). \]
Planetary Composition & Differentiation

The Hafnium (Hf) - Tungsten (W) isotope system tells us about the timing of core formation.

Hf decays to W with a half-life of 9 million years: \[ ^{182}\text{Hf} \rightarrow ^{182}\text{W} \]

**Hf is ‘lithophile’,** meaning it likes to stay with the silicates (the mantle). **W is ‘siderophile’,** meaning it likes to stay with Fe (the core).

As \(^{182}\text{Hf}\) decays (radioactively) to \(^{182}\text{W}\), the \(^{182}\text{W}\) stays with the metal to form the core, and the remaining \(^{182}\text{Hf}\) stays with the silicates to form the mantle.

\(^{182}\text{Hf}\) that stays in the mantle will continue to decay to \(^{182}\text{W}\), but the core is already formed, so it stays in the mantle!

If core formation is slow, then most \(^{182}\text{Hf}\) decays to \(^{182}\text{W}\) and the \(^{182}\text{W}\) has time to go into the core, so very little \(^{182}\text{W}\) will be observed in the mantle......
Core (metal) values yield chondritic value at time of segregation.

Epsilon can be considered a measurement of the ‘deviation’ from values that would be expected for chondritic composition.
But if core formation is rapid, then much of the $^{182}\text{Hf}$ will stay in the mantle. It will eventually decay (into $^{182}\text{W}$) in the mantle and we will see much higher $^{182}\text{W}$ in rocks.

We can apply the Hf-W measurement technique to rocks from Earth, the Moon, Mars, and asteroids to learn about how fast planetary bodies formed cores and experienced differentiation.

If you know how much Hf/W you started with, and you know the half-life, then you can measure what’s left and determine the number of half-lives or age of the material/process.

**Core formation appears to have been much more rapid than previously thought (<30 Myr).**
Meteorite Classification

Basic Types of Meteorites:

- Stony (93% of falls)
- Irons (6% of falls)
- Stony-Irons (1% of falls)

Classification

- **Undifferentiated** (chondrites) (stony meteorites; ~85% of falls; chemically similar to Sun)

- **Differentiated** (achondrites) (stony, iron, or stony-iron meteorites; ~15% of falls; have experienced igneous “processing”)

‘Primitive’ meteorites are stony meteorites and can be chondrites or special types of achondrites; the primitive meteorites are chemically similar to the Sun.
As depicted here, stony meteorites are much more common than irons and stony-irons.

The total number of stony-irons (pallasites & mesosiderites) is ~100 meteorites.

Chondrites (a type of stony meteorite) are the most common type found on Earth.
Meteorite Classification

All Meteorites

- stony 96.8%
- iron 2.6%
- mesosiderite 0.4%
- pallasite 0.2%

World
N = 39545

North America
N = 1734

Falls Only

- stony 94.5%
- iron 4.5%
- mesosiderite 0.6%
- pallasite 0.4%

World
N = 1090

North America
N = 178

Data from the Meteoritical Bulletin Database, November 9, 2010
Meteorite Classification: Iron Meteorites

(Note: This chart is slightly different from the previous discussion; here, irons and stony-irons are labeled separately from achondrites, but all are still considered differentiated.)
Iron meteorites are largely composed of iron and nickel metal, thus they are believed to represent the cores of differentiated asteroids.

Though rare compared to stony meteorites, irons were fairly common in meteorite collections:

- they are resistant to weathering
- they are more resistant to ablation during passage through the atmosphere
- they were often easier to find because they look very distinct (stony meteorites, on the other hand, can often look like typical terrestrial rocks)

The Willamette meteorite, housed at the American Museum of Natural History, is the largest one to ever be found in North America. Transported to Oregon by glacial floods?
Iron Meteorites

Historical classification scheme for iron meteorites was based on the patterns (Widmanstätten pattern) in the metal as observed in polished and/or etched slices. This pattern is related to the relative abundances of Ni and Fe.

Hexahedrites: no Widmanstätten pattern, relatively low Ni content

Octahedrites: distinct Widmanstätten pattern, average Ni content

Ataxites: no Widmanstätten pattern, high Ni content, pretty rare
Iron Meteorites

However, a new (and more scientifically meaningful) classification scheme has emerged.

Iron meteorites are now classified based on their chemical composition.

Specifically, they are classified by their relative proportions of Gallium, Germanium, & Iridium.

This classification has produced roughly ~12 ‘unique’ types of iron meteorites, where each type is believed to represent a unique ‘parent body’ (the source asteroid).

Scientists still go back and forth about the specific number/types of iron meteorites, but the classes run from I - IV with various subclasses (IA, IIAB, IVB, etc.)
Meteorite Classification: Stony-Iron Meteorites

(Note: This chart is slightly different from the previous discussion; here, irons and stony-irons are labeled separately from achondrites, but all are still considered differentiated.)
Stony-Irons: Pallasites & Mesosiderites

Stony-Iron meteorites are subdivided into 2 major types:

- **Pallasites**: composed of Fe-Ni metal and silicate (mostly olivine)
- **Mesosiderites**: composed of Fe-Ni metal and silicate (olivine, pyroxene); *breccias*

Because these meteorites consist of metal and silicate, they likely represent *fragments of core-mantle boundaries* in asteroids or possibly planetesimals.
The traditional view of pallasite formation is that represent differentiated bodies (olivine mantle and metallic core).

Impacts then broke up the parent body to create iron meteorites (cores) and stony-iron meteorites like the pallasites (core-mantle mixtures).

But new data suggest that iron meteorites have very different cooling rates than the pallasites, so maybe they are NOT from the same parent body.

Alternative hypothesis:
The solid cores were separated from the remaining (metal) melt and mantle by large impacts. The pallasites could come from many different bodies with different cooling histories.
Stony-Irons: Pallasites & Mesosiderites

This large pallasite was found near Fukang, China.

Marvin Killgore & the Fukang pallasite

Slices typically sell for ~$40 a gram.

The original mass was ~1000 kilograms.

You do the math.....
Differentiation of Iron Meteorite Parent Bodies

Core formation ages for magmatic iron meteorites

- IC: (-3.63 to -3.35)
- IIAB: (-3.43 to -3.23)
- IID: (-3.95 to -3.24)
- IIIAB: (-3.40 to -3.28)
- IIIE: (-3.41 to -3.33)
- IIIF: (-3.35 to -3.00)
- IVA: (-3.43 to -3.28)
- IVB: (-3.50 to -3.46)

Age relative to CAIs (Ma)

Early estimates had lower $^{182}\text{W}/^{184}\text{W}$ in irons than initial SS value...what? (extra $^{182}\text{W}$ from s and r processes!)

Within error, data show that iron parent bodies formed very fast and on same timescale as chondrules...core formation within 2 Myr of SS formation.

Timing of events relative to CAI (oldest materials) will depend on how well we ‘know’ the $\varepsilon^{182}\text{W}$ of CAI.

[Burkhardt et al., 2008]

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[Burkhardt et al., 2008]
To summarize:

Dust and small fragments stick together to form a planetesimal, and this planetesimal begins to differentiate: Fe & Ni sink to the center and the silicates form the mantle.

This process happens relatively rapidly (maybe <30 Myr after the Solar System begins to form).

Iron meteorites are believed to represent the cores of disrupted asteroids.

In the past, stony-iron meteorites were believed to come from the core-mantle boundary of disrupted asteroids....but perhaps they form by reassembling of destroyed objects.

Not all planetesimals will become planets: some shatter, others break apart into small lumps, asteroids are formed.
Timing of Accretion & Core Formation

[Diagram showing the timing of accretion and core formation for various celestial bodies, with annotations for Mars (S), Mars (NC), IVA, IAB, IVB, IVA, IAB, IIAB, IIIAB, Vesta, Earth, and Moon.]

Data from Jacobsen (2005) - Table 2; Figs. 5, 6, 7, and body text.
Breakdown of Stony Meteorites

Stony Meteorites

World
N = 38263

Data from the Meteoritical Bulletin Database, November 9, 2010
(Note: This chart is slightly different from the previous discussion; here, irons and stony-irons are labeled separately from achondrites, but all are still considered differentiated.)
Happy Valentine’s Day!
Chondrites are stony meteorites that have not been melted or experienced differentiation. This means that they come from asteroids or other parent bodies that did not separate into metal cores and silicate mantles.

Therefore, their bulk chemical composition is very similar to the original composition of the material that formed the Solar System (the solar nebula/molecular cloud).

There are 3 major types of chondrites:

- Enstatite (E) Chondrites
- Ordinary (O) Chondrites
- Carbonaceous (C) Chondrites

Many have experienced metamorphism (heating) or alteration by water. The degree of thermal or aqueous alteration determines the ‘class’ of the meteorite.

Certain asteroids have been linked to these classes of meteorites, but these associations are not ‘proven’, and it is still uncertain if these asteroids are the true parent bodies.
The petrologic type of a chondrite is a number from 1-6 that signifies the degree of aqueous or thermal alteration.

Low numbers represent aqueous alteration and are only associated with certain types of carbonaceous chondrites.

Higher numbers represent thermal metamorphism and are associated with a variety of chondrites.

Note that only a subset of the C chondrites have experienced aqueous alteration.
Stony Meteorites: Chondrites: Enstatite Chondrites

Enstatite (E) chondrites:

- these rocks formed in a very oxygen-poor environment (reduced, not oxidized)

- oxygen-poor environment is indicated because Fe and S are not in oxidized states (Fe occurs as metal and S as sulfides)

- chondrules in these meteorites are abundant in the pyroxene enstatite (MgSiO$_3$)

- they often exhibit evidence of heating (thermal metamorphism) on their parent body

- these meteorites are a relatively rare type of chondrite
Ordinary (O) chondrites:

- the most common type among meteorite finds

- 3 types of ordinary chondrites, grouped by their Fe and metal content:
  
  **H:** High-Fe content, fair amount of Fe-metal, contain pyroxene & olivine, most common type

  **L:** Lower-Fe than H type chondrites, less metal, contain pyroxene & olivine

  **LL:** Low-Fe, Low metal, Fe is mostly in olivine and pyroxene

- many have experienced metamorphism (heating)

- certain asteroids have been identified as possible parent bodies for ordinary chondrites
Carbonaceous (C) chondrites:

- They contain some of the most primitive material in the Solar System.

- Some (but not all) C-chondrites are similar in bulk composition to the solar nebula.

- C-chondrites are classified into different groups based on their compositions and the degrees of thermal metamorphism or aqueous alteration that they have experienced.

- Many of the C-chondrite groups are named after a well-known meteorite in that group (CM chondrites, for instance, are named after the Murchison meteorite).
The Sun’s photosphere emits radiation, and we can measure this radiation using spectroscopic techniques.

When we plot the chemistry of the CI carbonaceous chondrite meteorites against the composition of the solar photosphere we see that they are very similar.

Therefore, these meteorites are believed to be representative of the chemical composition of the original material from which the Solar System formed. For some of the elements in the Sun that we can’t measure directly, we use the CI chondrites to infer their abundance in the Sun.
The CI chondrites, which have experienced the most extensive aqueous alteration, are chemically the most similar to our Sun. Other types of chondrites are clearly different.
C chondrites are composed primarily of the major elements that are common to all asteroids and terrestrial planets, but the CI and CM chondrites also have some rather unique components:

- **water**
- **clays** (evidence of aqueous alteration)
- **carbonate minerals** (evidence of interaction with CO$_2$-bearing fluids)
- **organic material**, including amino acids (do not require ‘life’, but they are the building blocks)

The ‘matrix’ in chondrites (fine-grained material around the clasts) is a complex mixture of high and low-temperature minerals, aqueous alteration products like clays, carbon-rich material, etc.

It is interesting that the most aqueously altered chondrites (CI) have few or no chondrules, and they have been severely altered by water at low temperatures since their initial formation.

**Yet these are the meteorites that are chemically most similar to the solar nebula!**