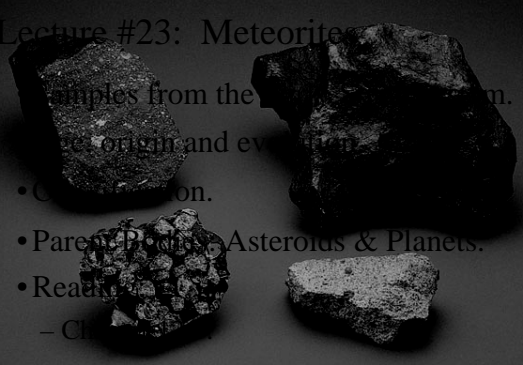


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## Lecture #23: Meteorites

Samples from the ...  
 ... origin and evolution ...

- Classification.
- Parent Bodies: Asteroids & Planets.
- Reentry ...  
 – Chondrites



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## The Main Point

Meteorites are small pieces of asteroids (and other bodies) that have impacted the Earth and that provide us with direct information on the original building blocks of the solar system.

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## Meteorites

- Free “Mini Sample Return Missions”.
- Do rocks really fall from the Sky?

*“I would rather believe that two Yankee professors would lie rather than stones would fall from heaven.”*  
 – Thomas Jefferson

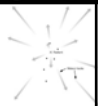


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## Definitions


- A **meteoroid** is any object which orbits the Sun on a collision course with another planetary body.
- A **meteor** is a bright streak of light in the sky, sometimes called a “shooting star” or “falling star”, produced as atmospheric friction burns up the outer layers of a meteoroid. A large, bright meteor is called a **fireball**.
- A **meteorite** is a fragment of one planetary body that lands on another planetary body.



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## or Find?



- A **fall** is a meteorite that was actually observed falling and then was collected. (Thus, usually not very weathered or altered by Earth's wind, water, and rain).
- A **find** is a meteorite that was not seen to fall but was found on the ground some time later. (Antarctic finds may have fallen 10,000 to 700,000 years ago).
- Only about 10% of meteorites in our collections are **falls** (in contrast, >20,000 Antarctic **finds** in the last 10 years).

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## Meteorite Taxonomy

Class	% occurrence of meteorite types		
	Falls	Finds	Antarctic
Primitive Stones	88%	51%	85%
Differen. Stones	8	1	12
Irons	3	42	2
Stony-Irons	1	5	1

- **Stony** (most common type)
  - Some "primitive", others differentiated.
  - A few have compositions like the mantles & crusts of the terrestrial planets.
- **Stony-Iron** (rare--easily weathered, eroded)
  - Contain roughly equal mixtures of rock and metal.
  - Remnants of the mantles of previously-formed parent bodies?
- **Iron** (less rare)
  - Dense metallic objects.
  - Large % of finds because they are harder to weather away.
  - Remnants of the cores of previously-formed parent bodies.

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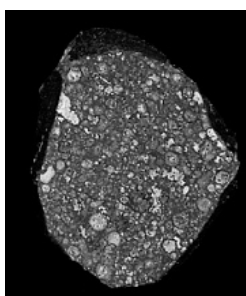
## Types of Stony Meteorites

- **Ordinary Chondrites**: most common meteorite type, some contain **chondrules** or condensed grains from the primitive solar nebula, heated to various levels.
- **Carbonaceous Chondrites**: are the most primitive type of stony meteorites (completely unprocessed), many contain **chondrules**, and are possibly samples of the original "starting material" for planets and asteroids.
- **Achondrites**: are the most heavily processed stony meteorites, and have undergone differentiation and igneous processes on larger parent bodies. Processing has destroyed/melted the chondrules.

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## Chondrules



- Millimeter-sized spherical deposits scattered throughout a dark background "matrix".
- Found only in the most primitive chondrites.
- Spherical shape: implies that these deposits were once molten droplets.
- The oldest stuff in the solar system! (4.6 b.y. +)

Chondrules may have been condensed from the original gaseous solar nebula and then melted, but their origin is *controversial*.

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## Composition of Chondrites

- Each dot is a particular element
- Y-axis: The Sun
- X-axis: Chondrites
- The slope of the line is 1 (correlated!)
- Chondrites are made of the same "stuff" as the Sun!

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## Where do Meteorites Come From?

- Most are pieces of *parent bodies* in the asteroid belt or near-Earth space that were either broken up or destroyed by impacts.
- Some may be pieces of comets.
- A very few are pieces of the Moon.
- A very few are pieces of other planets (Mars)
  - Recent discovery: the planets "trade" rocks!

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## Parent Bodies

"Primitive"  
Unprocessed

unsorted mix

Most Chondrites

Differentiated,  
Processed

lighter rock

metal

Achondrites

↓

Stony-Irons

↓

Irons

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## Differentiated Meteorites

- **Irons:**
  - Contain Fe-Ni alloys & Fe-S inclusions.
  - Characteristic cooling patterns ("Widmanstätten")
    - Cooling rate allows estimate of *parent body size!* (rate  $\approx 1/\text{size}$ ).
    - Typical parent body sizes: 70 to 200 km radius (asteroidal).
  - Pieces of the cores of differentiated parent bodies.
- **Stony-Irons:**
  - Mixtures of Fe-Ni and silicate rocks.
  - Pieces of the boundary between the rocky mantle and metallic core of differentiated parent bodies.

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## Meteorite Origins

- Evidence for asteroidal parent bodies:
  - Spectra of many meteorites resemble spectra of asteroid surfaces.
  - Orbits of some fireballs can be traced back into the asteroid belt.
  - Theoretical modeling shows that there are some gravitational "conveyor belts" (resonances) between the asteroid belt and the inner planets.

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## Asteroid & Meteorite Connections

- Some meteorites are samples of asteroids...
- They provide direct information on the early conditions of the solar system.
- They provide direct information on the interiors of asteroids and planets.
- Some meteorites have been found to be related to specific asteroids or even planets.

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## Asteroid & Meteorite Connections

- Asteroid spectra (black lines) similar to certain meteorite spectra (red lines).
- General trends:

Asteroid	Meteorite
C types	Carbonaceous chondrites
S types	Ordinary chondrites
	Anomalous achondrites
M types	Irons
V types	Achondrites

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## Meteorites probe different asteroid source regions...

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## Meteorites from the Moon!

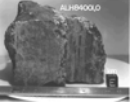
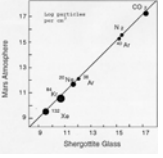
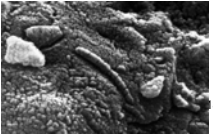


- Impacts can eject rocks off the Moon at speeds > escape velocity--some of these rocks fall to Earth.
- About 20 meteorites (out of >20,000) have been identified as Moon rocks from their chemistry and isotopes.
- Most are *breccias* from the highlands.
- A few are *mare basalt* (volcanic) samples.
- These rocks are free (but random) samples of different places on the Moon than those sampled by Apollo missions:
  - Provide additional (new) information on lunar composition.
  - May represent more "typical" lunar crust than the Apollo samples?

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## Meteorites from Mars!


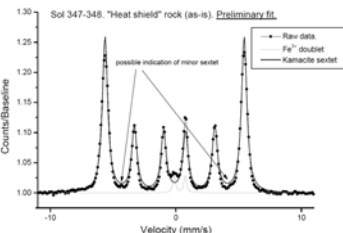




- Impacts eject rocks off larger planets too.
- ~24 meteorites have been identified as coming from Mars, based on composition, isotopes, and trapped gas bubbles.
- Samples of Mars! (but random & deep).
- Provide new data on crustal composition.
- Some meteoriticists believe that one of the Mars rocks contains *chemical and fossil evidence for life on Mars!*
  - **Extremely Controversial!**
  - **No Scientific Consensus!**

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## Meteorites on Mars!!!





- Discovered by Mars Exploration Rover team.

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## Summary



- Meteorites are rocks that fall from space:
  - Most are samples of asteroids, and provide a way to remotely study the asteroid belt.
  - Most are primitive (unprocessed) rocks, formed from the building blocks of the planets.
- Many meteorites must have come from differentiated parent bodies that no longer exist:
  - The only surviving record of the solar system's birth!
- A few meteorites are from the Moon and Mars and provide new and controversial data!

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