Meteorites and cosmochemical abundances

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(Dated: Thursday 9th May, 2019)

Goals We will understanding the abundances, distribution, and behavior of the elements in planets, nebula and the Sun. There are different types of meteorites (chondrites, achondrites, irons, etc), some of which are the building blocks of the planets. Meteorites record a variety of ages that inform us about their formation, formation ages of their components, and their differentiation histories. Meteorites also inform us about nebula processes, the timing of accretion, and the behavior of elements in the nebula and in planetary bodies (i.e., refractory vs volatile elements; lithophile, siderophile, etc).

Questions to consider:

1. why do we study meteorites?
2. what are the different types of meteorite?
3. what principles inform the classification of meteorites?
4. what was the "pre-formation" setting for the solar system (the ISM (interstellar medium), stellar nursery)?
5. what do we know of the local astro-mineralogy in the ISM?
6. what was the initiation event that started our solar system?
7. what were the important time-space aspects of the accretion disk?
8. what is meant by — what is the age of the Earth?

Meteorites, the cosmos, and the early solar system — *t_0 plus 10^0 to 10^8 years*
Where do meteorites come from? Some are from Mars and the Moon, however, many are from the asteroid belt and beyond (e.g., the trojans orbiting Jupiter at L4 and L5 positions, Kuiper belt objects). How do we identify the location for where a meteorite was derived?

Time t_0 refers the start of the solar system. How do we know this? Much of the architecture of the solar system was developed in the first 10^8 years (0.1 Ga). How do meteorites tell us about the nature, timing, and processes involved in solar system formation? How did it all start?

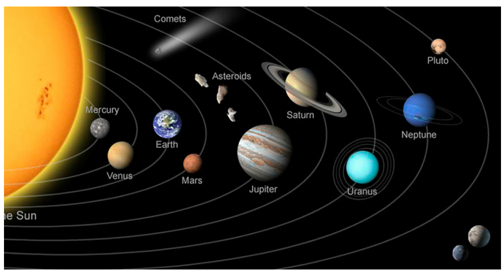


Figure 1: Solar system

We know little of the pre-solar system environment that existed some 4.57 Ga ago. The local ISM (interstellar medium) was likely populated with gas-dust clouds, which were locally feed by SLRs (short lived radionuclides, e.g., ^{60}Fe and ^{26}Al) from a range of galactic sources (e.g., asymptotic giant branch (AGB), supernovae, Wolf-Rayet (WR) stars) that supply specific proportions of r-, p- and s-process nuclides, particularly some short-lived isotopes and supernovae and/or neutron mergers (sources of r-process nuclides)). The relative proportions of the SLRs in the early solar system provides constraints on the inputs and triggers for the initiation of the solar system. Models envisage solar system formation by a triggering event that causes a gravitational collapse of a molecular gas-dust cloud in the ISM by adding to its mass and momentum. The types of triggers include (1) supernovae, (2) neutron mergers, (3) self-collapse of a dense molecular cloud, and/or (4) a winds from a Wolf-Rayet (W-R) Bubble (a nebula surrounding a W-R star, a highly luminous and rare stellar object). The shockwave from such an event had to be sufficiently close to fragment a portion of an ISM gas-dust cloud, but not too close, otherwise a shockwave from such an event would simply fragment and scatter the gas-dust cloud. Recent suggestions conclude that the proportions of SLRs could be the product of stellar winds from a W-R star that ejects ^{26}Al in its winds during its rapid evolution, with the ^{60}Fe contribution reflecting the galactic background. This scenario is consistent with the presence and relative abundance of key short-lived isotopes (e.g., ^{26}Al ($t_{1/2}$ = 0.7 Ma), ^{41}Ca ($t_{1/2}$ = 0.1 Ma), ^{60}Fe ($t_{1/2}$ = 2.62 Ma), etc.) documented in some of the earliest nebular condensates.

Trigger and Star formation: ... the details are likely to change in the coming years

1. Strong winds from the early evolutionary stages of the nebula bubble of a Wolf-Rayet star can interact explosively with nearby interstellar gas-dust clouds (or diffuse nebulae) adding mass and momentum causing collapse of this cloud or cloud fragment followed by its corotation. The addition of mass and the energy from the explosion results in an increase of gas pressure in the cloud, which causes gravitational collapse.
2. The collapse of the proto-stellar cloud continues as long as its gravitational energy is dissipated through radiation. As matter density increases the cloud becomes opaque to its own radiation, with the excess energy being imparted into the nebula dust within the cloud. The dust, thus enhances further cloud collapse.
3. Eventually, due to the centrifugal effects, the cloud's density increases towards the center and ultimately a central core will heat and dissociate H_2 molecules and ionize, H^+ and He^+ in the nebula. Infall to the central plane continues until the gas becomes hot enough for the internal pressure to support the protostar against further gravitational collapse. As accretion reaches near completion the system becomes a protostar.
4. With increasing accretion onto the protostar its density and temperature becomes high enough to support deuterium fusion. Further infall of material into the protostar initiates the production of bipolar jets, which accommodates shedding of the excess angular momentum of the infalling material leading to star formation.
5. Ultimately, in the case of our solar system, hydrogen fu-

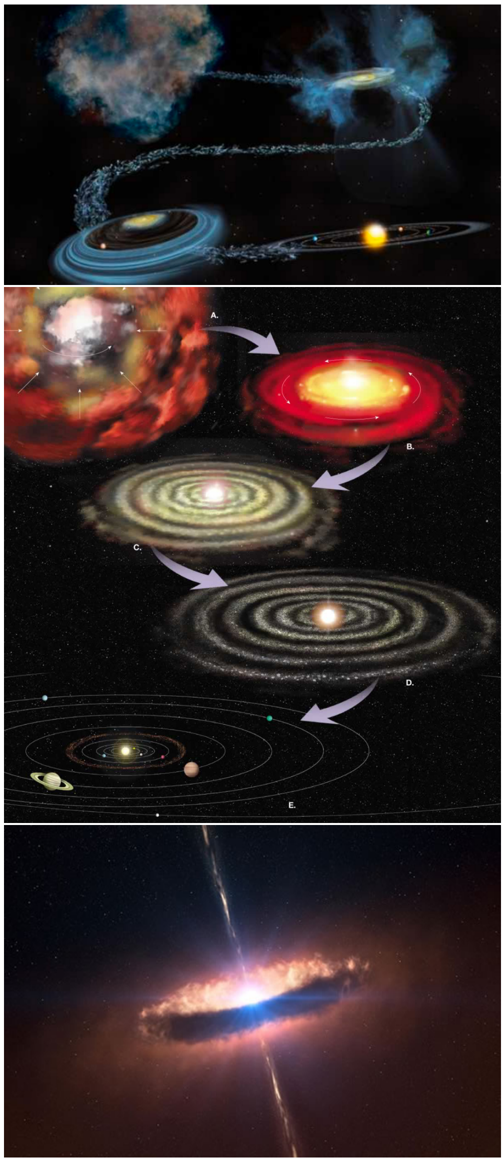


Figure 2: Solar system formation

sion begins in the core of our Sun and the remaining accretion disk is cleared away.

Evidence: Much of the evidence for the Sun's formation, bipolar jets, and the existence and evolution of a disk and its eventual dissipation comes from astronomical observations. The existence of short-lived radionuclides in earliest solar system is an important part of this story. CAIs (Ca-Al-inclusions) are a critical piece of evidence in the story. These are the oldest known objects in the solar system (i.e., defining t_0 read as t_{zero}); their mineralogy and mineral texture reveals that they are rapidly crystallized objects, condensed from a high temperature environment in the nebula. Their ages are established by isochrons (a graph that reveals the parent - daughter isotope systematics and age of a sample) using ^{26}Al: a p-process nuclide [production via ^{25}Mg(p,γ)^{26}Al]. ^{26}Al decays via β^+ (18%) and ϵ (electron capture, 82%) branches to ^{26}Mg, with a half-life ($t_{1/2}$) of 0.7 Ma. This decay reaction is exothermic with an energy release Q of 4.004 MeV; it provides significant heating to planets and planetesimal in early solar system.

The meteoritic record

10^2 -10^5 yr: nebula disk fm, sun ignition, CAI, planetesimal form, differentiation (core-mantle)
10^5 -10^6 yr: planet are growing, Jupiter controls mass distribution in the nebula
10^6 -10^7 yr: disk evolves and is lost, planet accretion continues, magma ocean(s)
10^7 -10^8 yr: Moon fm, late accretion, vigorous early mantle convection, crust & atmosphere fm

t_0 plus 100,000 years

t_0 is defined as the oldest dated material in the solar system: i.e.,the age of CAI formation
Time-space distribution and evolution of gas in disk: condensation sequence
Time-space variation in disk composition: Sun's composition - inner vs outer shell?
The Sun: layered? chemically heterogeneous — likely. How and why?
Timescales of planetesimal, chondritic parent bodies, and planet formation
Where and when did planetesimal and Jupiter form?
Grand Tack model, role for gas giants (Jupiter migration), volatiles in the solar system

10^6 - to a few 10^7 years after t_0

what is the role of short-lived isotopes? [Chondrite fm ages]
Redox vs time: secular variation in disk composition
Rapid planetary differentiation: stories from ^{182}W in iron meteorites
Astro-mineralogy of accretion disks lateral and temporal variability: Mg/Si of planets
Dispersal of the solar nebula (likely some 3 to 6 Ma after t_0)
Earth's most significant differentiation event: core formation (likely 10 to 50 Ma post t_0)
Core formation: when [^{182}Hf(β^-,β^-)^{182}W]?, how deep [Ni/Co]? What was the fO$_2$?
Did collisional erosion play a role in shaping Earth's composition?

10^7 to a few to many 10^8 years after t_0

Moon formation: when, Giant Impacts — how many, how deep? The evidence?
Magma oceans: when, how many, how deep? The evidence?
Initial differentiation of the BSE (bulk silicate Earth): formation of a surface crust
Core-mantle exchange: what has happened since core fm?
Early vs late accretion rates: what is the dM/dt (Mass)
Evolution of the atmosphere and hydrosphere
Nice model: 2^{nd}stage migration of gas giants established, gas giants drive late accretion?

Solar system Attributes:
The Sun — the mass of the solar system — 10^6 kg > Earth; 10^3 kg > Jupiter
Jupiter: it is 2.5 times more massive than all other planets combined
Jupiter: if it ended up growing 14 times larger, it would have be a Brown dwarf
The spectral match between the solar photosphere and chondrites (great, but there are problems!)
Inner versus Outer solar system — distribution of volatiles
Astro-mineralogy of accretion disks (variations in olivine/pyroxene proportions)
Behavior and classifications of elements in disks and planets
Refractory elements (Ca, Al, Ti, etc), major elements (Mg, Fe, Si, Ni)
Moderately volatile elements (e.g., K, Rb, S) and volatile elements (H, C, N, O?)
Lithophile (silicates), **siderophile** (core), **chalcophile** (throughout) elements
Atmophile/hydrophile elements (e.g., H, C, N, O) — mostly found at the surface

Observations from Meteorites:
Chondrites (primitive) vs Differentiated types (achondrites, irons, stony irons)
Age of meteoritic components, meteorites and planets [a quick stop, details filled in later?]
Redox classifications of chondrite types (86% of all Falls):
  Oxidized : carbonaceous (4%)
  Reduced : enstatite (2%)
  Intermediate : ordinary (80%)
Earth is reduced, its oxidation state is between Enstatite and Ordinary chondrites
Mg-Si-Fe: disk stories about metals vs silicates and olivine vs pyroxene

Cosmic abundances and how is it determined? Solar spectra - absorption at particular wavelengths tells us what elements are there – the intensity of the absorption lines correlates with abundance. We see that the sun and other stars show similar proportions of elements – ”cosmic abundances”. However, there exists a problem regarding the metallicity of the Sun. To astronomers, metals are elements heavier than H and He. The *solar metallicity problem* states that the Sun’s fraction of metal is 1.8%, as determined by Helioseismology, or 1.3% , as determined by absorption spectroscopy. More recently, the measured composition of solar wind particles find a solar metal fraction of 1.8% and the latest neutrino spectroscopy finding also favor a higher metallicity value, all leaving the absorption spectroscopy measurements isolated. Here again, we need more data and new approaches to sort out these issues.

Meteorites and their classification :
Simple, but not useful: stones, stony irons, irons
Preferred classification (using chemical and physical ”genetics”):
a) chondrites - composed of several different materials of different ages and origins. These rocks are chemically primitive, undifferentiated, composed of rock and metal. They are the sedimentary conglomerates of the nebula. Most have abundant chondrules, which are mm-sized spherical condensates/melt droplets- chemically primitive, undifferentiated.
b) achondrites – lacks chondrules, differentiated composition
c) irons and stony irons – metallic cores of pre-existing planetesimals – differentiates

Chondrites :
These are the most abundant type of meteorite (can be considered in terms of falls vs. finds, more than 27,000 samples). These meteorites provide the important insights into under-

standing the composition, origin, evolution, and age of the Solar System. Chondrites are composed of a markedly heterogeneous lithology, composed of Ca-Al-inclusions, olivine aggregates, chondrules (20-80%; except CI1 chondrites with no chondrules) and matrix. There are 3 major groups: Carbonaceous, Ordinary, and Enstatite chondrites, and two lesser known ones: Kakangari type and Rumurutiites. On average chondritic meteorites are known for having the relative constant proportions of refractory elements (elements with condensation temperatures >1350 K)within all groups, but different absolute abundances of the elements between groups. The major elements (Mg, Si, Fe, Ni) have similar temperatures and bracket the refractory elements and volatile elements (condensation temperatures >1250 K).

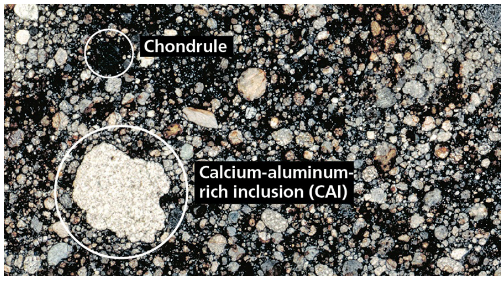
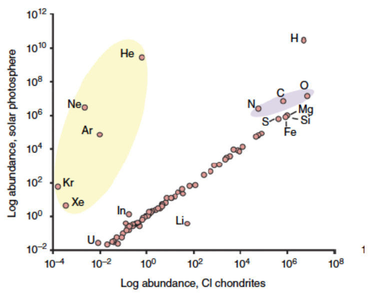
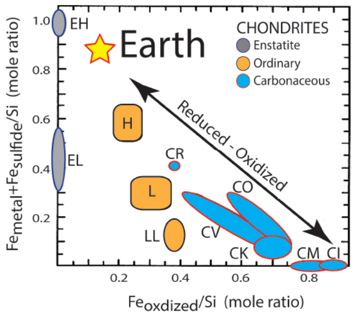


Figure 3: Chondrite thin section

The composition of the CI1 chondrites matches that of the solar photosphere (when normalized to 10^6 atoms of Si). Thus, we can consider the CI1 carbonaceous chondrites some of the most primitive material in our solar system. Note, the mass of the Sun, is essentially the mass of the solar system (i.e., Jupiter contributes only 1 part per thousand to the solar sytem). Given this, the average solar system is equivalent to the composition of the CI1 chondrites and the solar photosphere. Refractory vs volatiles: behavior in nebula [based on temperature scale, >1350 K]. Volatile element is one that has a low condensation temperature (condensation T VGs). If gas phase blown away (e.g. T-tauri stage of sun), might expect to see differing concentrations of volatile elements with distance from sun.
Redox state plays an important role



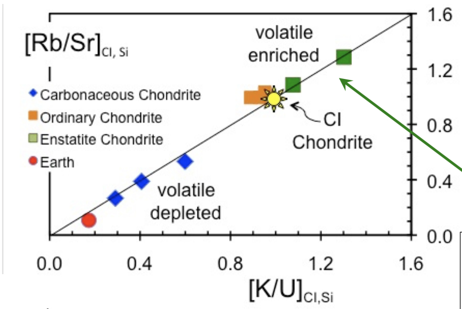


Two-fold classification of elements

Refractory	>1400 K
“Si, Mg, Fe, Ni…	1350 to 1250 K
Moderately volatile	1250 to 650 K
Volatile	<650 K

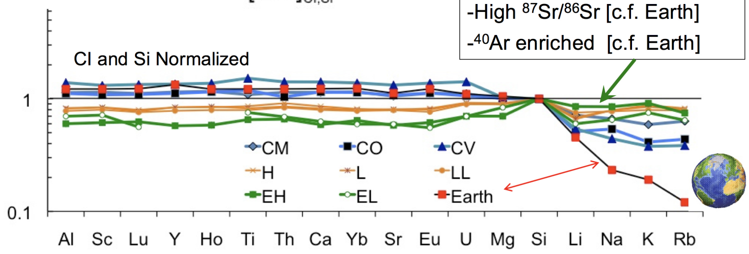
classified	affinity	where
Siderophile	iron	core
Lithophile	oxide	mantle
Chalcophile	sulfur	mostly core

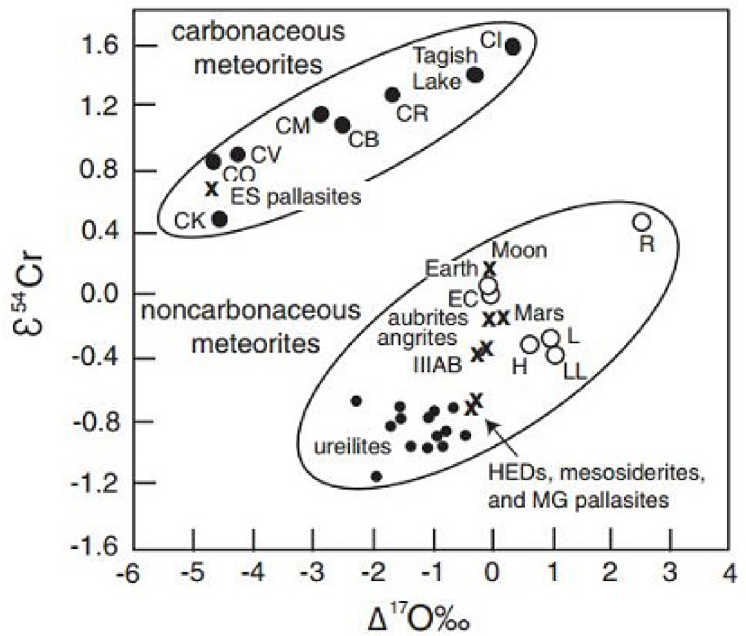
Redox conditions in the Solar System…..

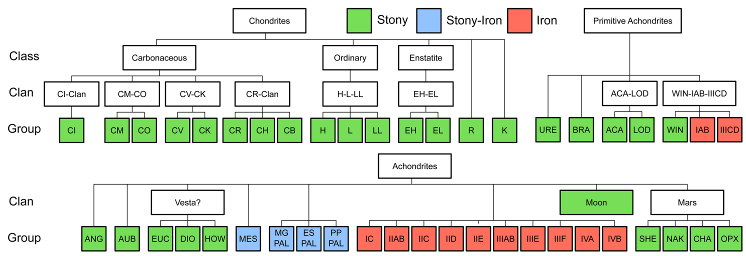


Volatiles (*alkali metals*) in Chondrites

Enstatite Chondrites
-enriched in volatile elements
-High $^{87}Sr/^{86}Sr$ [c.f. Earth]
-^{40}Ar enriched [c.f. Earth]




carbonaceous meteorites
CI
Tagish Lake
CR
CM
CB
CV
CO
ES pallasites
CK
noncarbonaceous meteorites
R
Moon
Earth
EC
aubrites
Mars
angrites
IIIAB
L
H
LL
ureilites
HEDs, mesosiderites, and MG pallasites
ε54Cr
Δ17O‰


Chondrites
Stony
Stony-Iron
Iron
Primitive Achondrites
Class
Carbonaceous
Ordinary
Enstatite
Clan
CI-Clan
CM-CO
CV-CK
CR-Clan
H-L-LL
EH-EL
ACA-LOD
WIN-IAB-IIICD
Group
CI
CM
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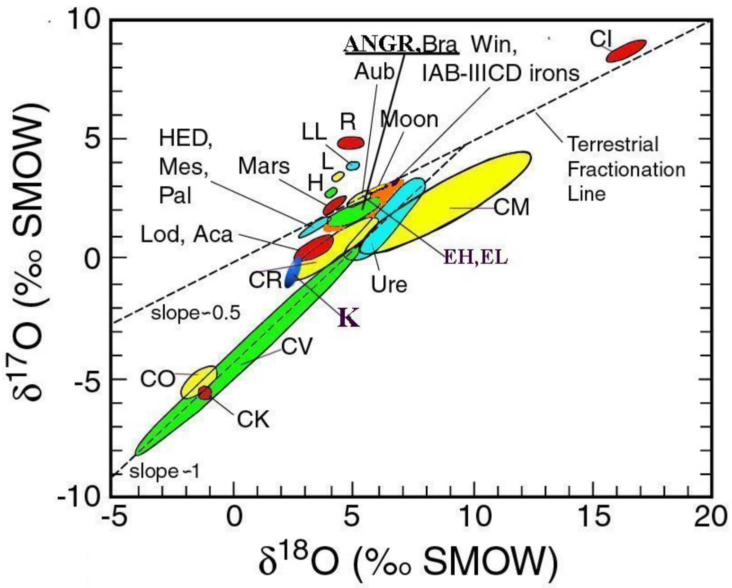
ANGR,Bra
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HED,
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Pal
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Terrestrial Fractionation Line
CM
Lod, Aca
EH,EL
CR
Ure
K
slope-0.5
CV
CO
CK
slope-1
δ17O (‰ SMOW)
δ18O (‰ SMOW)