Wed. Sept. 20, 2017

- Reading:
  - For Friday:
    - Connelly et al. 2012, "The Absolute Chronology and Thermal Processing of Solids in the Solar Protoplanetary Disk." 338: 651-665.
    - Simon et al., 2011, "Oxygen Isotope Variations at the Margin of a CAI Records Circulation Within the Solar Nebula." Science, 331: 1175-1178
    - (links to electronic verson on class web site)

- Today:
  - For Monday Sept. 25 and following days
    read Chapter 4 (The Moon) of Christiansen and Hamblin (on reserve).

Some Current Questions
Regarding Early Solar System #3

Implications of the “Nice” model and Grand Tack for dynamics and orbits:

Grand Tack:

Interaction of Jupiter (and Saturn) with residual gas initially causes it to migrate inward , clearing out most planetesimals beyond 1AU. Later migration (once it is tied to Saturn) causes it to migrate outward to its present location

- Migration may redistribute much of the material which eventually forms the terrestrial planets
- It may also repopulate the asteroid belt with material from a range of locations in the solar system.
  - Inner belt material from inner solar system
  - Outer belt material from beyond Jupiter

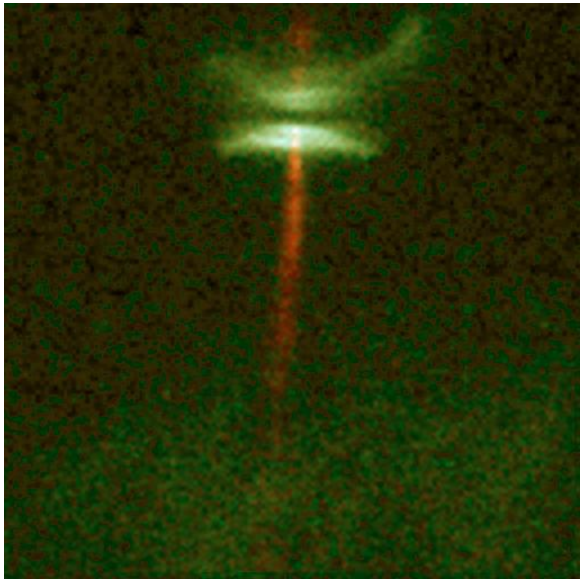
Beyond the "Standard Model" of Equilibrium Condensation

- While meteorites indicate something like the Equilibrium Condensation Model occurred, fine details don't match
  - Already have a mixture of different T components in chondrites
  - Detailed isotopic anomalies give hints about incomplete mixing in early solar nebula, and "local" processes which alter equilibrium predictions.
  - Need to have some mixing of material from different regions to supply water, other volatiles to the Earth (D/H ratio constraints too)
  - Actual size of Mars seems too low
  - Uranus and Neptune take too long to form at present location
  - Asteroid belt seems mixture of types which should be more spread out

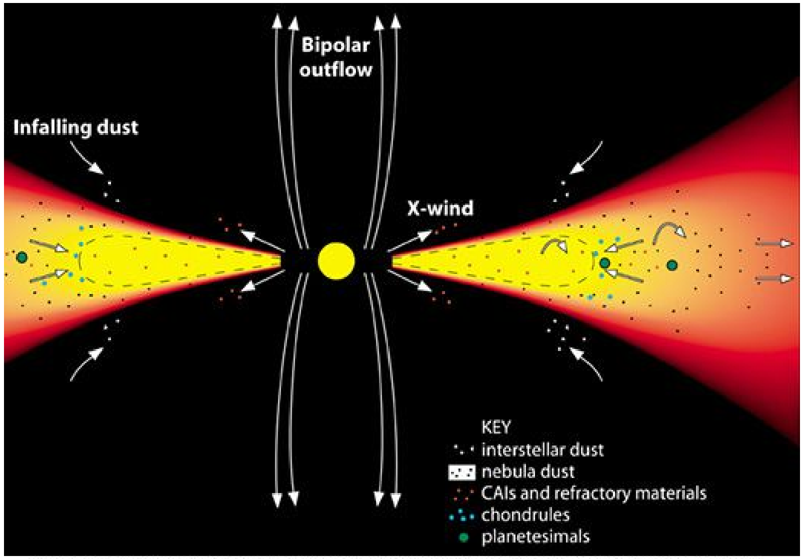
Circulation in the solar nebula?

- Other star-forming disks show jets of material emerging perpendicular to the disk
  - The thick disk blocks any wind in the plane of the disk
  - Complex processes near the star create jets from top and bottom of disk
  - Jets provide a way for the system to lose angular momentum

- Some material within the main disk may migrate in towards the star, then be carried back out in the "X-Wind" to circulate multiple times.



HH-30 (Edge-on Disk and Jets) Hubble Image



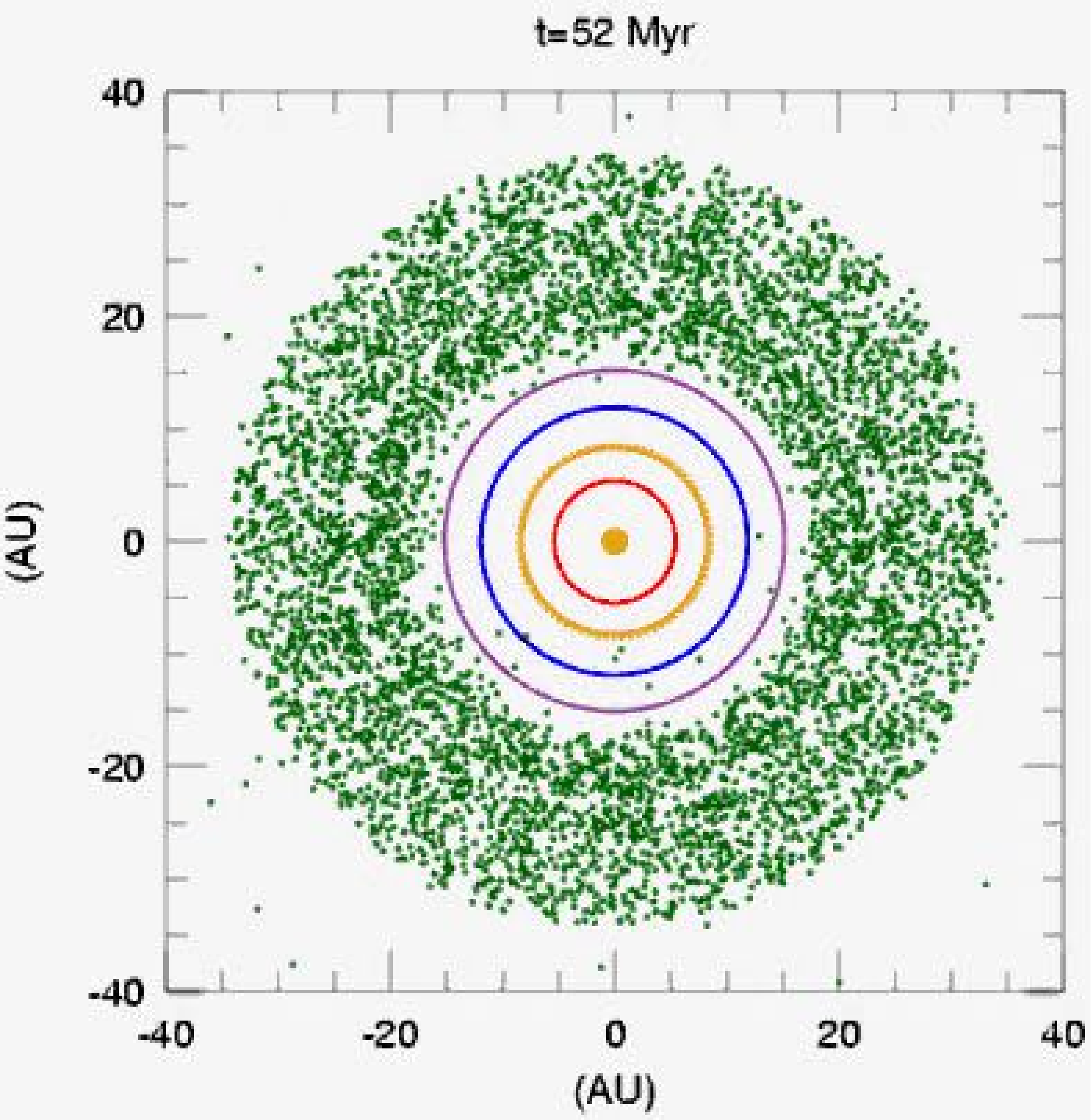
(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

From <http://www.psrd.hawaii.edu/Dec01/Oisotopes.html>

Nice Model, Grand Tack (more later)

- Nice Model:
  - After the gas is gone, you have slow migration due to scattering of remaining planetesimals
  - Jupiter migrates inward as it looses energy by ejecting some planetesimals from the solar system
  - Saturn (and Uranus and Neptune) migrate outward as they scatter planetesimals to Jupiter
  - If Jupiter and Saturn migrate into a 1:2 resonance then their orbits become significantly eccentric, and that produces significant gravitational effects on the rest of the system
    - Scattering of Uranus and Neptune outward
    - Scattering of icy planetesimals, and asteroids
    - Late Heavy Bombardment
- Grand Tack
  - Before above, while gas is still present, giant planets migrate inward
  - If Jupiter, Saturn go into 3:2 lock they can actually migrate outward
  - Model has Jupiter migrating inward to 1.5AU, truncating inner disk at 1AU, then during "tack", migrate outward to present location
  - Truncated disk explains relative size of Earth, Mars
  - Motion of Jupiter clears, then repopulates asteroid belt with both inner and outer disk material

Nice Model Simulation



Grand Tack Model Simulations

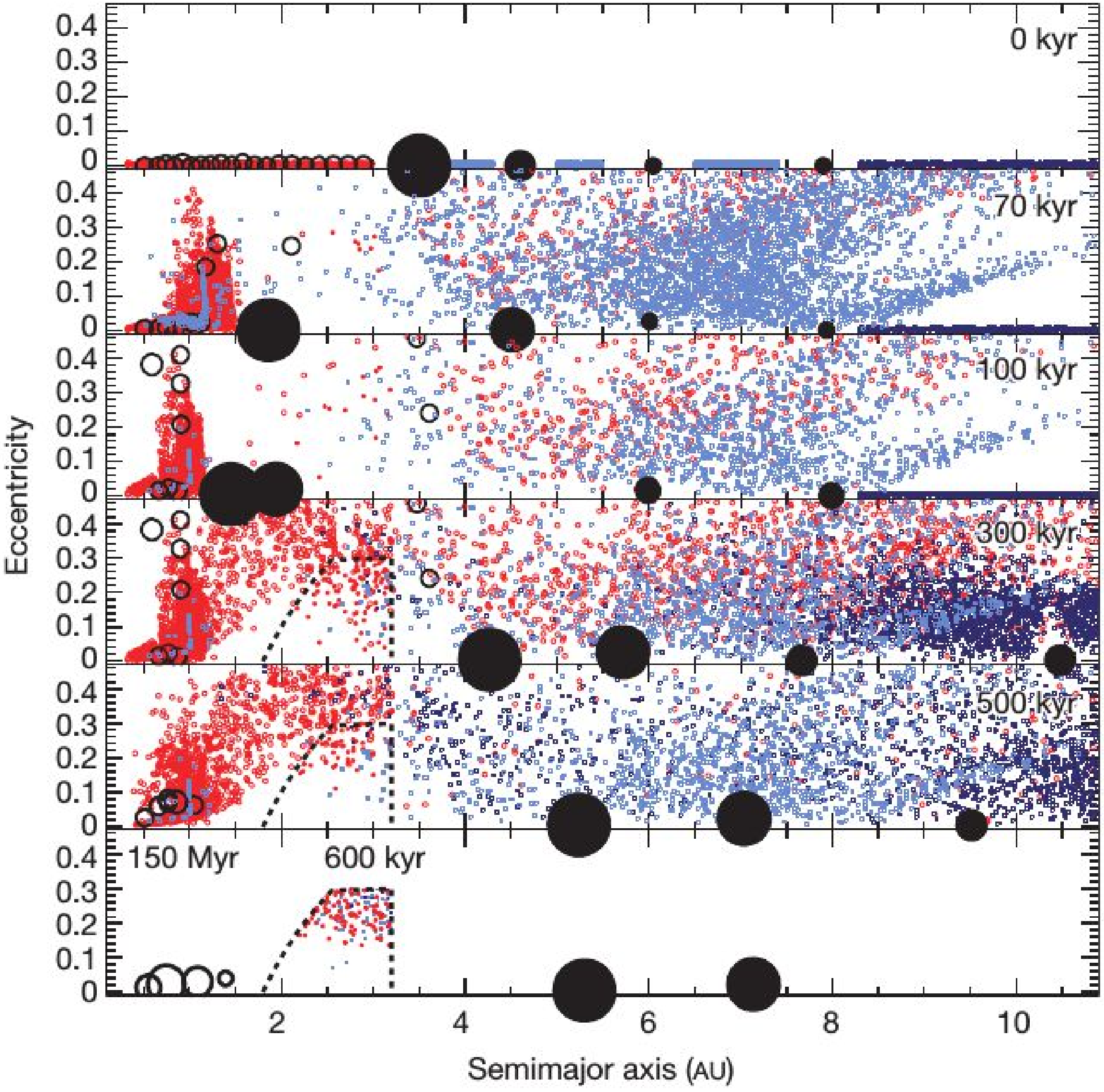


Figure 2 | The evolution of the small-body populations during the growth and migration of the giant planets, as described in Fig. 1. Jupiter, Saturn,

- Grand Tack:
  - Jupiter migrates inward to 1.5 AU, which truncates inner disk at 1 AU
  - Truncated disk gives right Mars/Earth size
  - Once Jupiter achieves 3:2 resonance with Saturn it "tacks" out to present location
  - Motion clears, then repopulates asteroid belt with mixture of:
    - red = inner disk planetesimals
    - blue= outer disk planetesimals

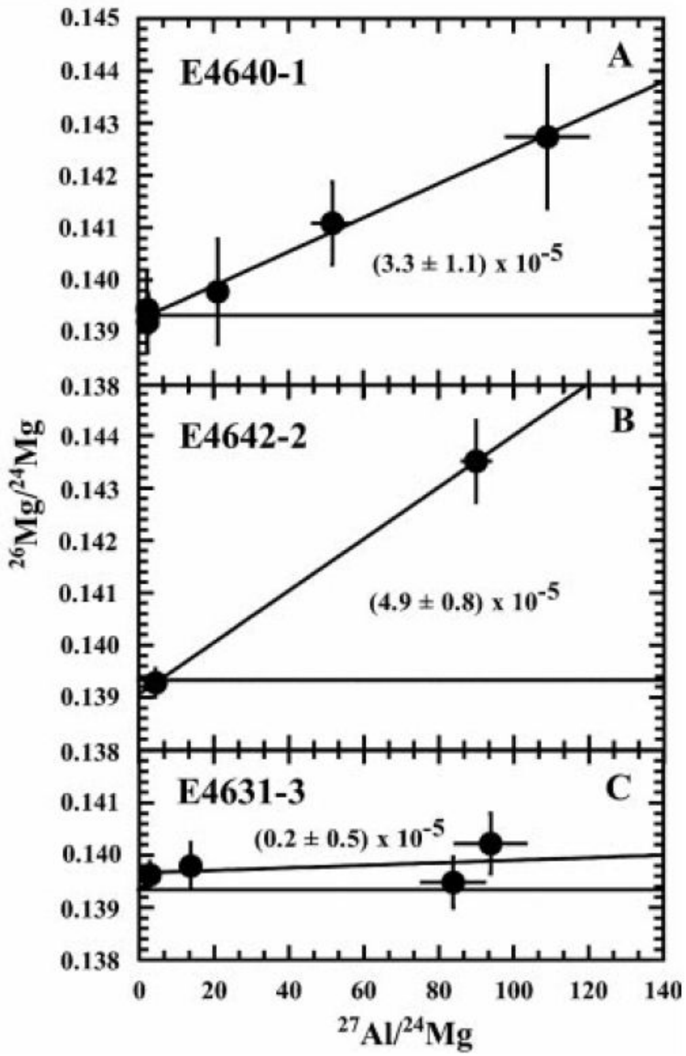
Walsh et al. 2011

Time-scale for CAI and Chondrule formation

- Initial results from ^{26}Mg anomalies and early Pb-Pb dates for CAI's and Chondrules (next few slides) suggested there was a few million year gap between the formation of the CAI's and the Chondrules

- More recent papers (Connelly et al. 2012) suggest that is too simple, and that chondrule formation began at the same time the CAI's condensed, but continued for a few million years.

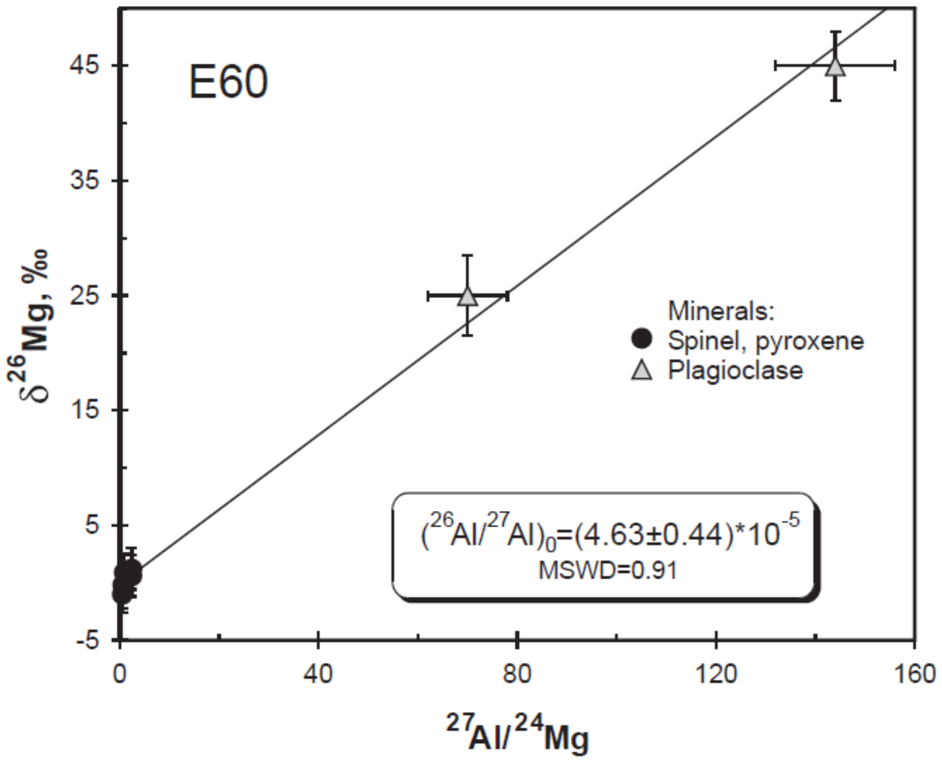
Timescales from ^{26}Al decay:



- Does the declining amount of original ^{26}Al truly measure the time of formation? If so can use
  $N = N_0 e^{-\lambda t}$ to get age.
- Most CAI's show initial ^{26}Al/^{27}Al abundance of ~5 × 10^{-5} while highest chondrules show ~1.5 × 10^{-5}.
- Difference of factor of 3.3 imples ~1.7 half-lives (so 1.7 × 0.73 My) passed between the two events.
- Some other isotopic anomalies (^{10}Be) suggest other effects could have produced short-lived isotopes and therefore corrupted the apparent time scale.
- Need way to test this using alternate dating technique

Guan et al. 2000 CAI abundences. Chondrules show even more of a drop in initial ^{26}Al/^{27}Al.

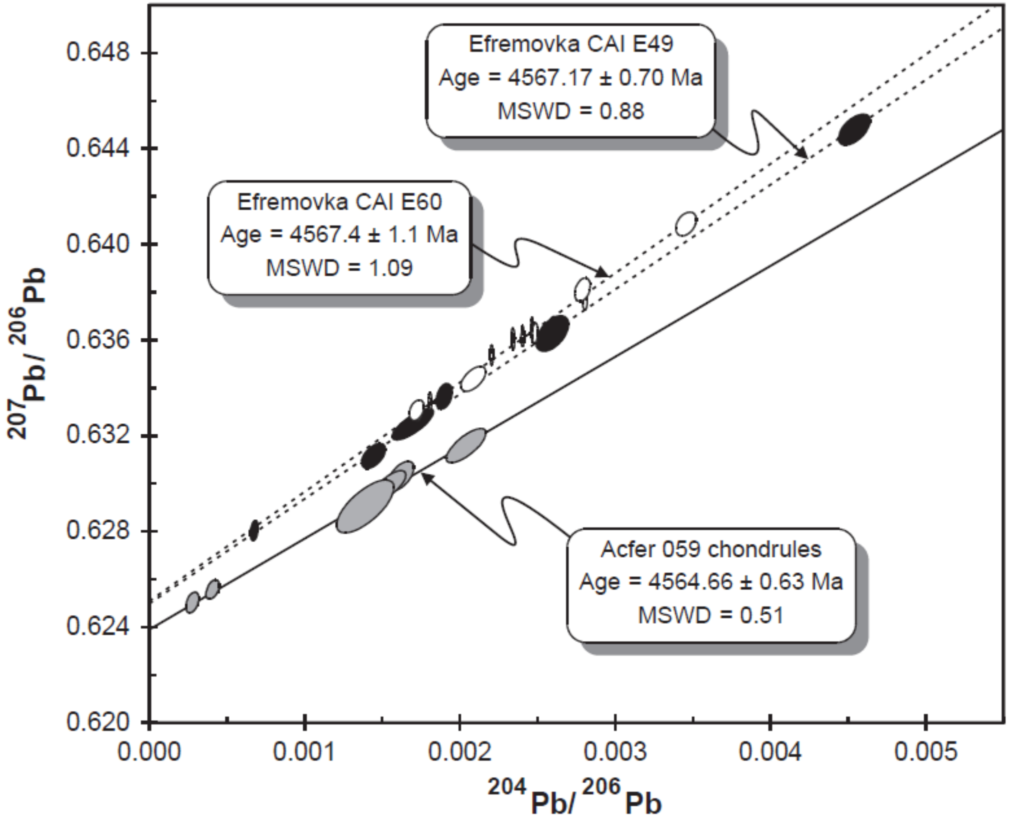
Is the implied ^{26}Al time scale correct? Amelin et al. 2002



Amelin et al. 2002

- Results of CAI's from Efromovka, a CV chondrite
  - Remember: CV means Vigarano-like chondrite
- They also analyze Chondrules from Acfer, a CR chondrite
  - CR means Renazzo-like
- They use a Pb-Pb radiometric dating technique to check relative ages of the CAI's and the Chondrules

Tests using the Pb-Pb system: Amelin et al. 2002



Amelin et al. 2002

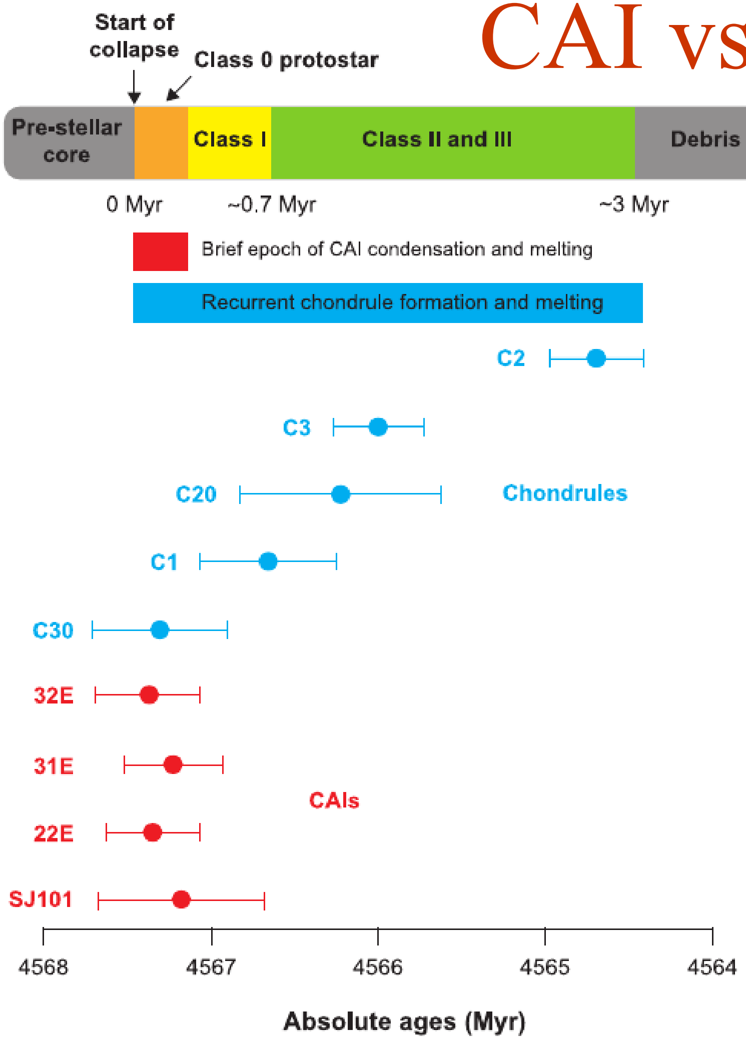
- ^{235}U → ^{207}Pb 0.713 Ga
- ^{238}U → ^{206}Pb 4.51 Ga
- ^{232}Th → ^{208}Pb 14.1 Ga
- ^{204}Pb non-radiogenic

- Using ratios of same element (rather than ratios of daughter / parent) eliminates error due to later chemical effects

- ^{204}Pb/^{206}Pb gives measure of initial Pb/U abundance ratio. (In limit ^{204}Pb → 0 mineral had no initial Pb.)
- ^{207}Pb/^{206}Pb (initially) increases with time because of faster ^{235}U decay
- Higher and steeper curves correspond to older ages

- Data suggest Efremovka CAI's are older than Acfer chondrules by 4567.3 – 4564.7 = 2.6 Ma, (they quote 2.5 ± 1.2 Ma) consistent with numbers implied by ^{26}Al decay

Connelly et al. 2012 evidence of CAI vs. Chondrule Age



Connelly et al. 2012

- Using Pb-Pb techniques Connelley et al. 2012 come to different conclusion:
  - CAI's all form early
  - Chondrules form over a range of times, starting at same time as the CAI's

Oxygen Isotope Fractionation by UV

- The excess ^{16}O seen in CAI's might be due to oxygen isotope fractionation in the solar nebula due to UV photons

- ^{16}O is far more abundant that ^{17}O or ^{18}O:
  - ^{16}O/^{18}O = 500 ^{16}O/^{17}O = 2,500

- The sun will produce UV which will be absorbed by O, (or by gasses containing O, mostly CO).
- Because of the slight mass difference, the wavelength of the absorption features will be slightly different for ^{16}O and ^{17}O and ^{18}O.
  - The much larger abundance of ^{16}O means the photons absorbed by it will be used up long before the photons absorbed by ^{17}O or ^{18}O.
  - Beyond some critical distance from the sun, the outer ^{16}O will be shielded (from UV) by the inner ^{16}O, but the ^{17}O and ^{18}O will not.
  - In that "outer" region the ^{17}O and ^{18}O will be subject to very different (UV driven) chemical processes than ^{16}O, and so can be separated from it. For example dissociation of (^{17}O and ^{18}O containing) CO will produce much more active atomic O, but this will not happen with ^{16}O.

- Simon et al. (2011) presents evidence at CAI's circulate between regions with different oxygen isotope abundances.