The heterogeneous accretion of the solar nebula

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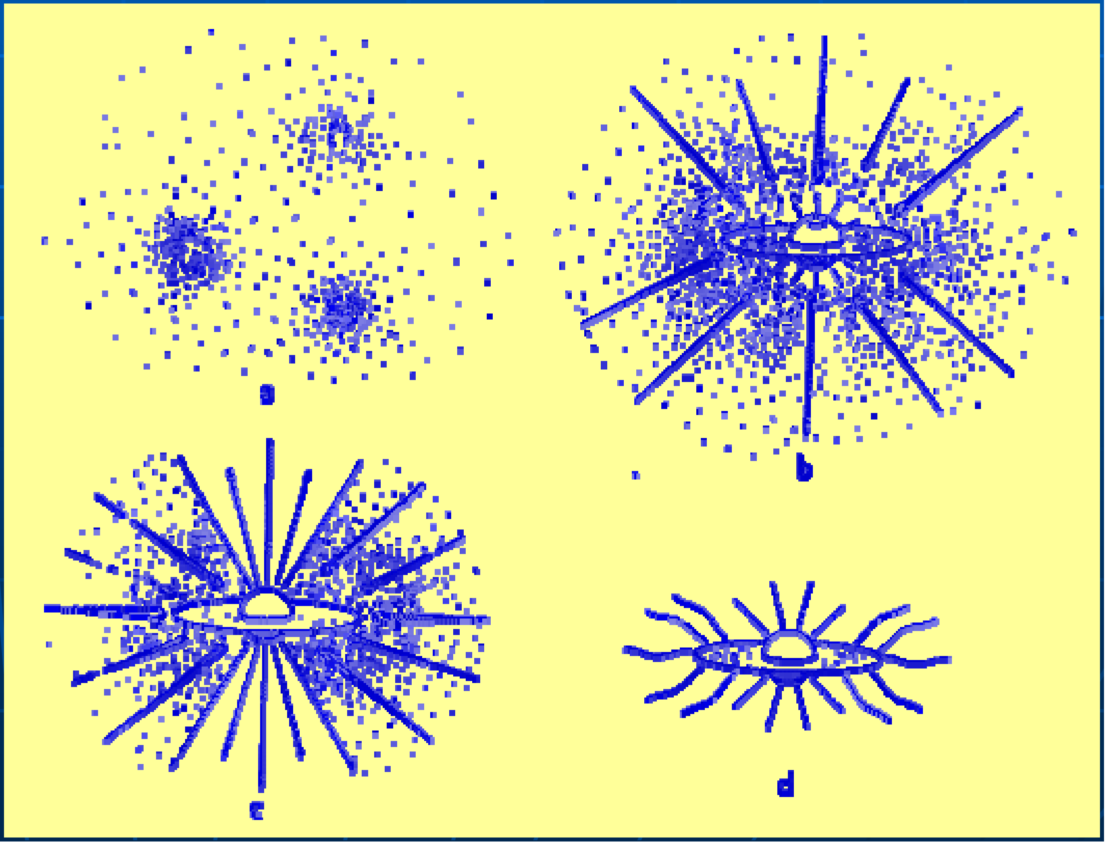
- Planetary matter (i.e., chondrites) formed from the last materials to fall into the solar nebula.
- This process lasted about 2 Ma.
- The chemical and isotopic compositions of these infalling materials changed with time.
- The infall appears to have been episodic, i.e., the rate changed with time

The heterogeneous accretion of the solar nebula

- Chondrites are the first rocks produced during planet formation; they consist of particles formed in the solar nebula.
- Chondrites form three clans, carbonaceous chondrites (CC), ordinary chondrites (OC), enstatite chondrites (EC); these differ in their abundances of refractory elements (Al, Ca) and in their isotopic compositions of O, Cr, Ti, Ni.
- The isotopic anomalies are non-mass dependent; they were inherited from the molecular cloud.
- ε^{54}Cr is positive in CC, Earth-like in EC and negative in OC
- The same sequence is observed for ε^{62}Ni and for ε^{50}Ti.
- The data require heterogeneous accretion of the solar nebula, and imply hiatus between periods of planetesimal formation.

The classic picture of solar-system formation

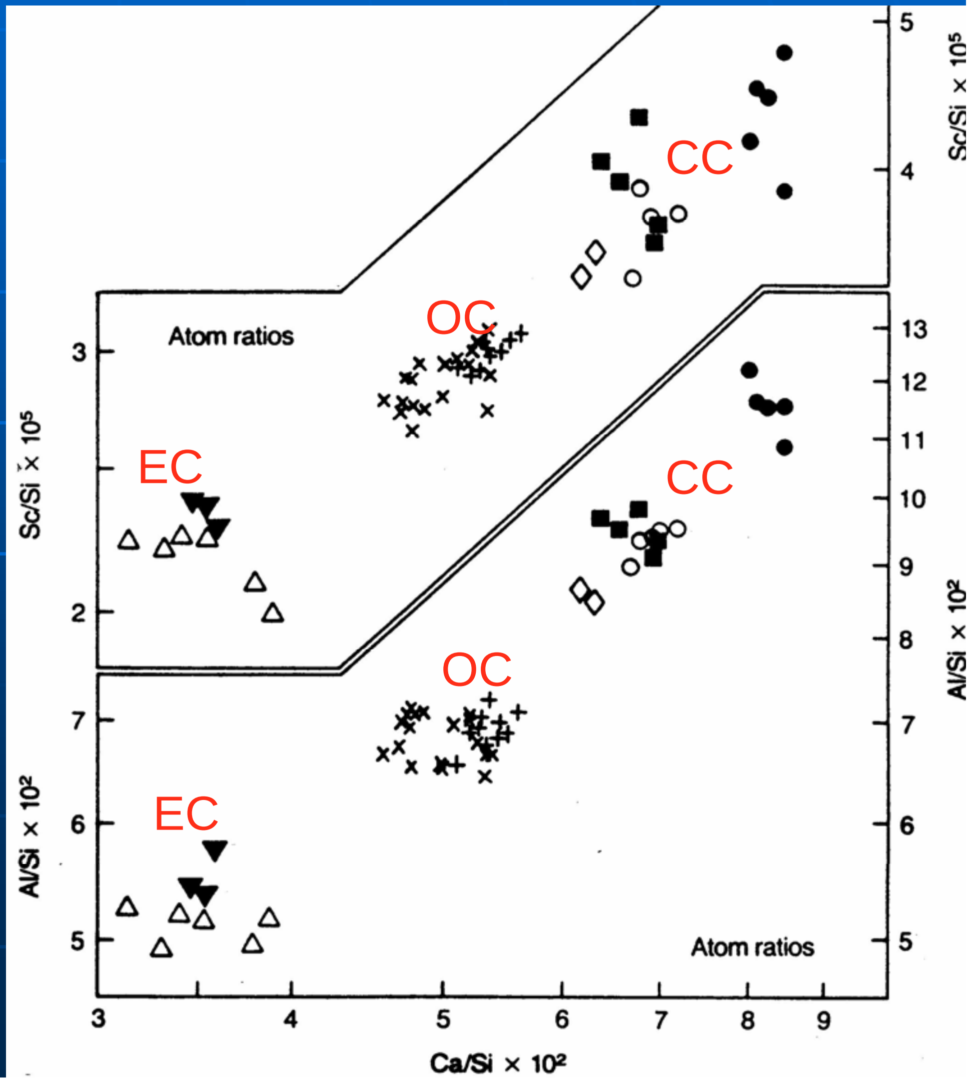
- In steps b, c and d it is commonly assumed that the collapse is symmetric and that the matter is well mixed.
- Chemical and isotopic composition data on chondrites show that such accretion occurred in pulses



cartoons from Shu, Adams and Lazaro (1987); length scale decreases from a through d.

Chondrites preserve a record of the solar nebula

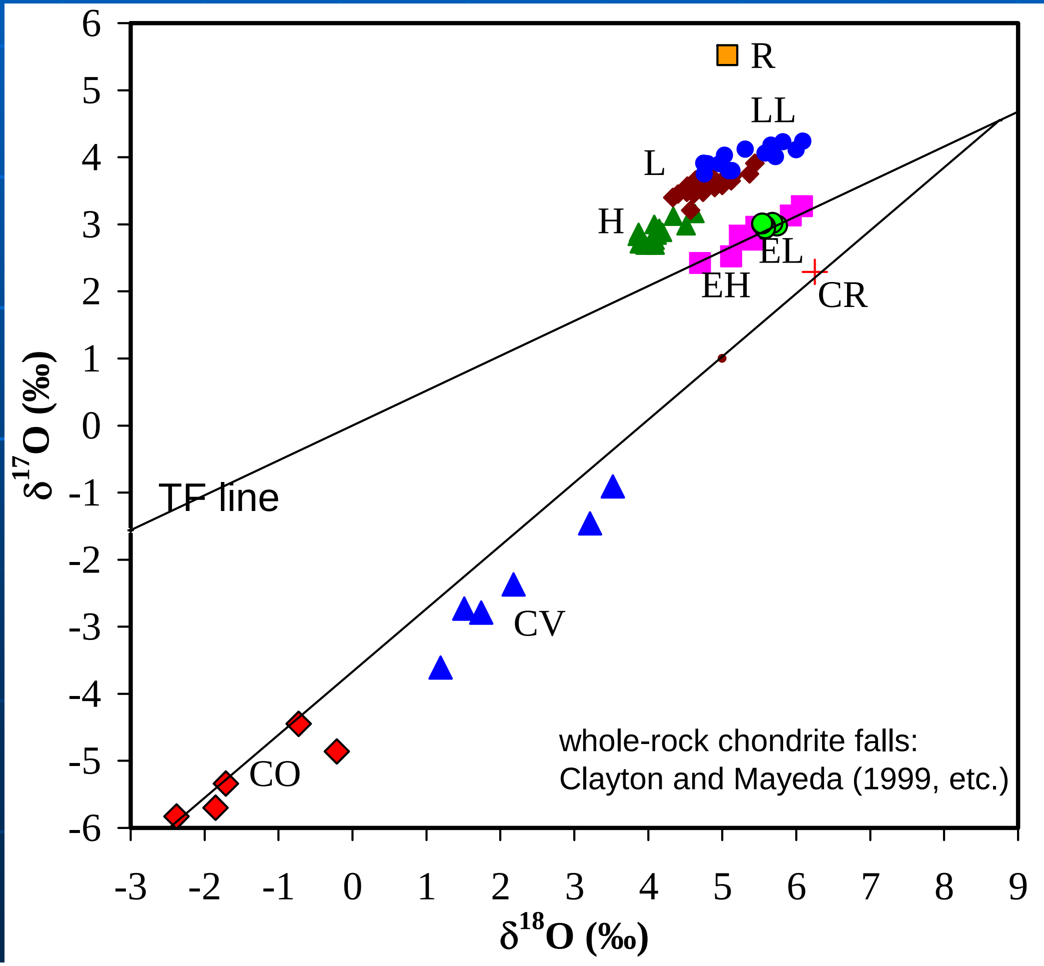
- Chondrite groups can be resolved in terms of several compositional and textural parameters.
- This example shows ratios of refractory lithophile elements to the common element Si (range is 2.5).
- Large hiatus observed.
- Hiatus appear to be real, not due to sampling.



EC = enstatite chondrites
OC = ordinary chondrites
CC = carbonaceous chondrites

O-isotope variations in whole-rock chondrites

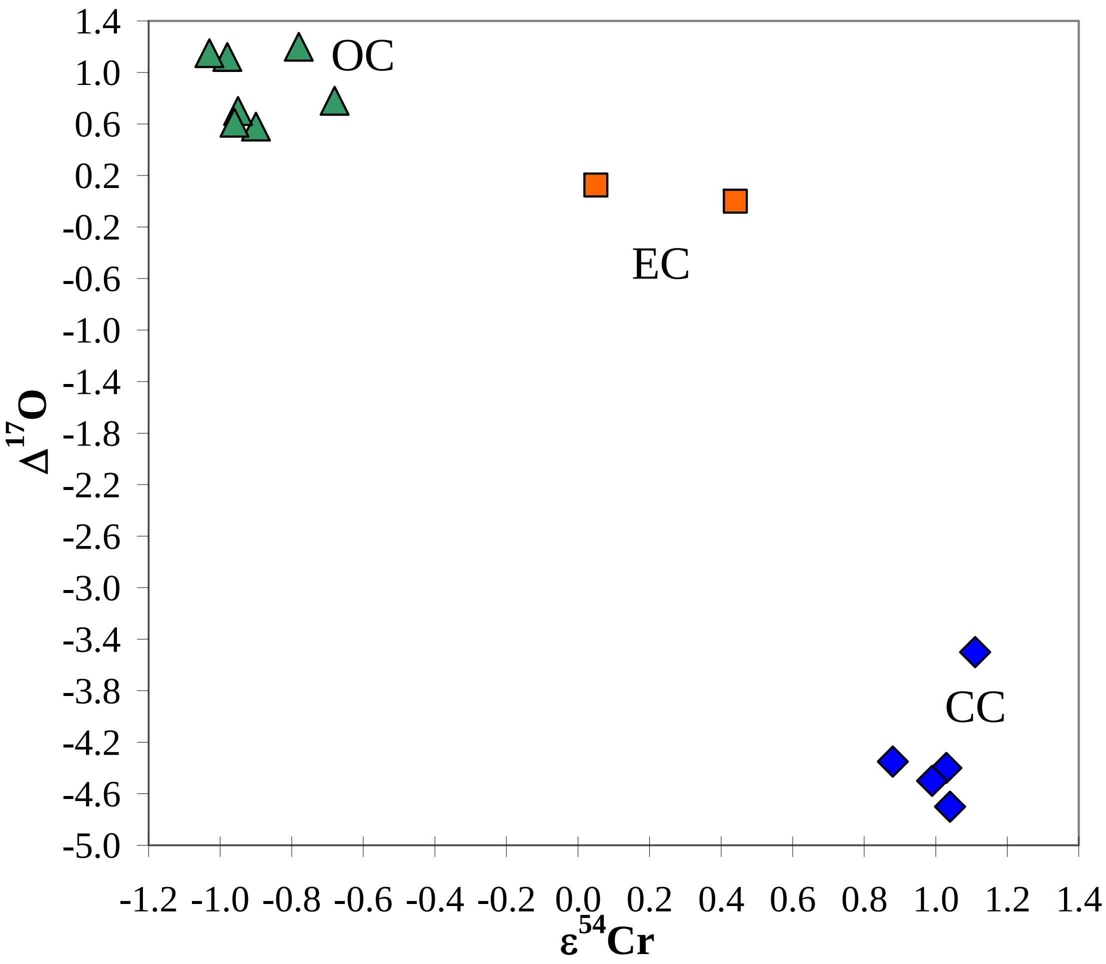
- This diagram shows chondrite fall data from Clayton and Mayeda for anhydrous chondrite groups.
- Whole-rock values for hydrated groups (CI, CM, CR) strongly affected by added H_2O.



range in $\Delta^{17}O$ is ~6‰

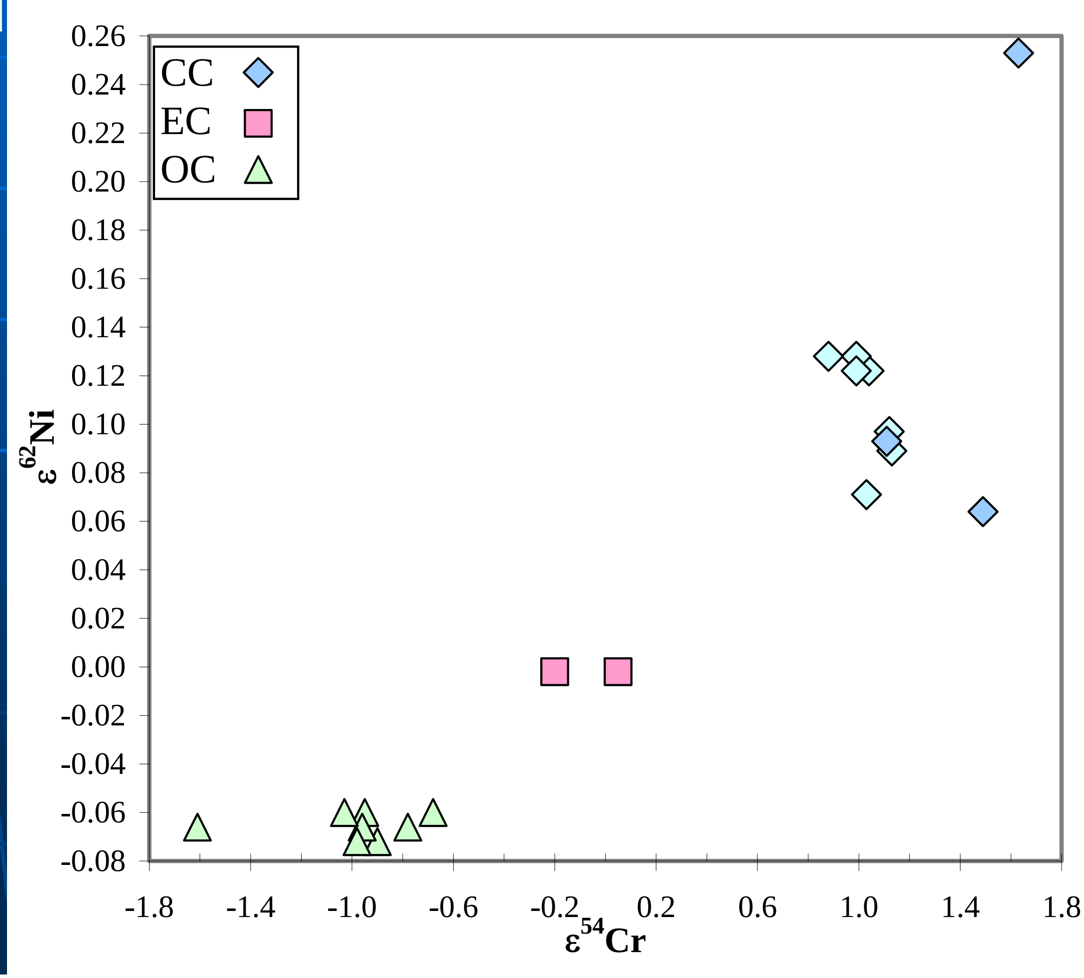
Compositional gaps in $\Delta^{17}O$ and $\varepsilon^{54}Cr$

- Large gaps between CC, EC and OC also in terms of $\Delta^{17}O$, and sequence same (EC in middle) as in $\varepsilon^{54}Cr$
- Models attempting to create these $\Delta^{17}O$ values in solar nebula are simplistic and implausible.
- Differences in $\Delta^{17}O$ and $\varepsilon^{54}Cr$ were inherited from the molecular cloud.



ε^{62}Ni and ε^{54}Cr are correlated

- Whole-rock ε^{62}Ni values correlate with our ε^{54}Cr values.
- These neutron-rich isotopes are produced in type-I supernovae.
- Note hiatus between CC, OC and EC.



Significance of the hiatus

- Do the compositional gaps represent incomplete sampling of the asteroid belt or real gaps in the compositions of nebular materials?
- Chondrites mainly come to Earth from the inner asteroid belt ($2.1 < a < 2.6$ AU) via the ν_6 and 3:1 resonances.
- This region is incompletely sampled, but the collection of small meteorites from Antarctica and from the hot deserts has added samples from many additional asteroids. Chondrites also contain foreign materials that help make the sampling more complete.

Heterogenous accretion of the solar nebula

- Classic picture of how chondrites formed is:
  a) start with a well-mixed homogeneous nebula
  b) devise processes to unmix the nebula to provide the variety observed in chondrites.
- <u>This picture is wrong</u>. The correct picture is:
  a) recognize that the nebula formed heterogeneously, both in terms of elemental ratios and in terms of isotopes;
  b) recognize that nebular accretion was a stochastic process, both in terms of composition and the rates of accretion;
  c) gather data that will clarify the variable rates of accretion, and the nature of the accreting parcels.

Formation of the solar nebula was very messy

- Rather than radially symmetric formation of the Sun from well-mixed materials we need to allow for large changes in compositions and angular momenta (7.2° tilt of solar axis!) of accreting matter.
- Such effects must occur for stars forming alone but be much more common for stars forming as members of large (>100) sets.

The bottom line

- Isotopic data require that the solar nebula formed heterogeneously.
- The composition gaps between clans (related sets) of chondrite seem best understood in terms of episodic accretion.
- Accretion was responsible for much of the turbulence in the nebula. Planetesimal formation could only occur during quiescent periods between pulses of accretion.