$^{238}U/^{235}U$ Variations in Meteorites: Extant ^{247}Cm and Implications for Pb-Pb Dating

G.A. Brennecka et al.

Science vol. 327, 22 Jan. 2010

Introduction

- The $^{238}U/^{235}U$ isotope ratio has long been considered invariant in meteoritic materials (equal to 137.88).
- This assumption is a cornerstone of the high-precision Pb-Pb dates that define the absolute age of the solar system.
- In this study, the authors
  - present high-precision $^{238}U/^{235}U$ ratios obtained from CAIs of Allende meteorite
  - demonstrate that this assumption is incorrect for these materials

Sample: CAIs of the Allende meteorite

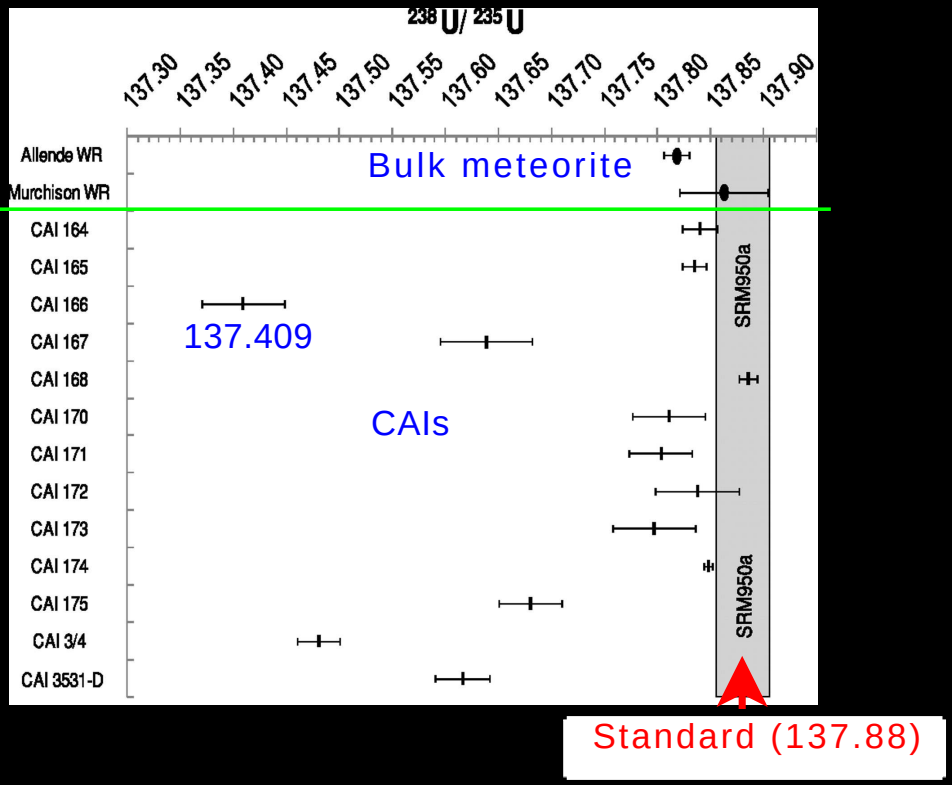
Allende meteorite - image by Matteo Chinellato

Calcium-aluminium-rich inclusions (CAIs) represent the first solids to condense from the cooling protoplanetary disk during the birth of the solar system

Methods

- Samples (CAIs) were separated from different sections of the Allende meteorite.
- Samples were dissolved in HNO_3, HF, and $HClO_4$.
- 5 % of each sample reserved for trace element measurements (REE patterns, Th/U and Nd/U ratios).
- Trace element measurements were performed with ICPMS.
- Uranium was separated with a chromatographic extraction method.
- Uranium isotope measurements were performed with MC-ICPMS.

$^{238}U/^{235}U$ isotope values for the samples

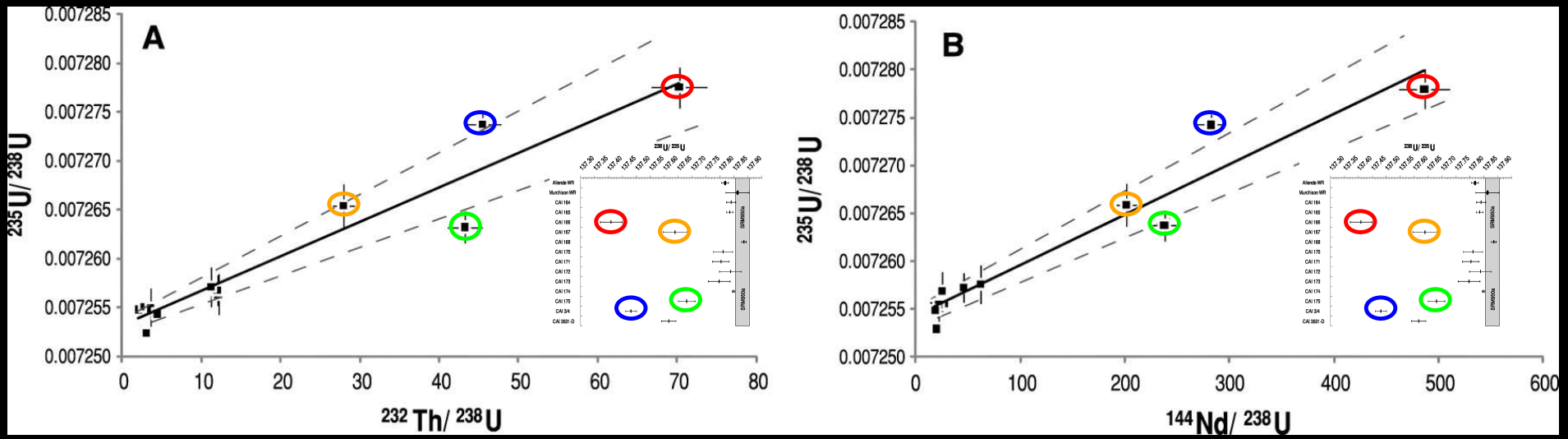


- Most CAIs differ outside uncertainties from SRM950a
- Five CAIs have significantly lower $^{238}U/^{235}U$ values

^{238}U/ ^{235}U variations in the samples

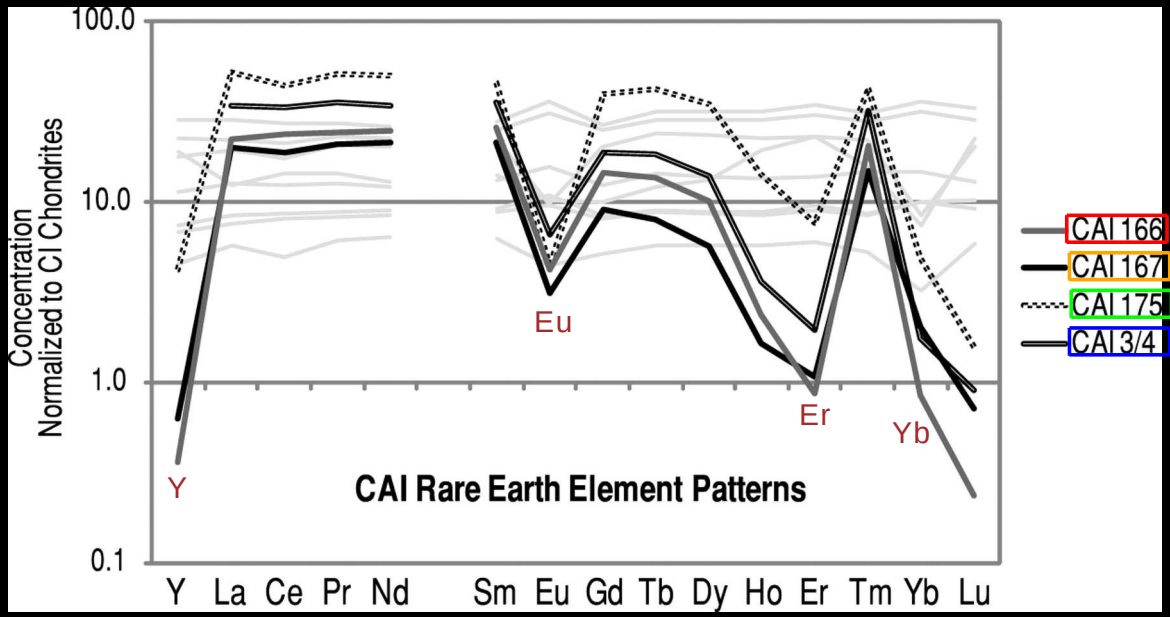
- Uranium isotope variations in meteorites may be produced by decay of extant ^{247}Cm to ^{235}U
- ^{247}Cm is only created in supernova (explosion of star) and decays to ^{235}U with a half-life of 15.6 My.
- If ^{247}Cm decay is the primary mechanism for ^{238}U/ ^{235}U variability, then materials with a high initial Cm/U value would contain a higher relative amount of ^{235}U than those with lower initial Cm/U values.
- Because Cm has no long-lived stable isotope, the initial Cm/U ratio of a sample cannot be directly determined.
- Because Th and Nd have similar geochemical behavior to Cm, Th/U and Nd/U ratios can be used as proxies for the initial Cm/U ratio in the samples

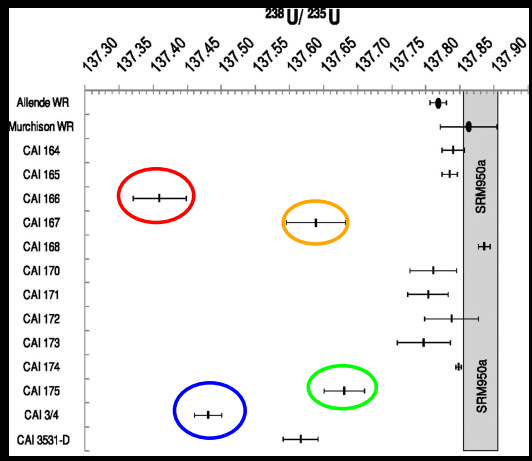
$^{232}Th/^{238}U$ and $^{144}Nd/^{238}U$ plotted vs $^{235}U/^{238}U$



- Large variations of the Th/U and Nd/U suggests that fractionation of Th and Nd from U occured in the early solar nebula.
- Th/U and Nd/U ratios correlate with reciprocal values of $^{238}U/^{235}U$
- The samples with a high initial Th/U and Nd/U values contains a higher relative amount of ^{235}U
- The correlation of $^{238}U/^{235}U$ ratios with proxies for Cm/U provides strong evidence that the observed variations of $^{238}U/^{235}U$ in CAIs were produced by the decay of extant ^{247}Cm to ^{235}U in the early solar system.

REE patterns of CAIs





- A special group of CAIs, called group II CAIs, are distinguished by a unique pattern of REE.
- The REE pattern suggests a complex condensation history involving fractional condensation.
- The four CAIs that have the highest Nd/U and Th/U ratios (as well as the lowest $^{238}U/^{235}U$) are all classified as group II CAIs.

Pb-Pb dating

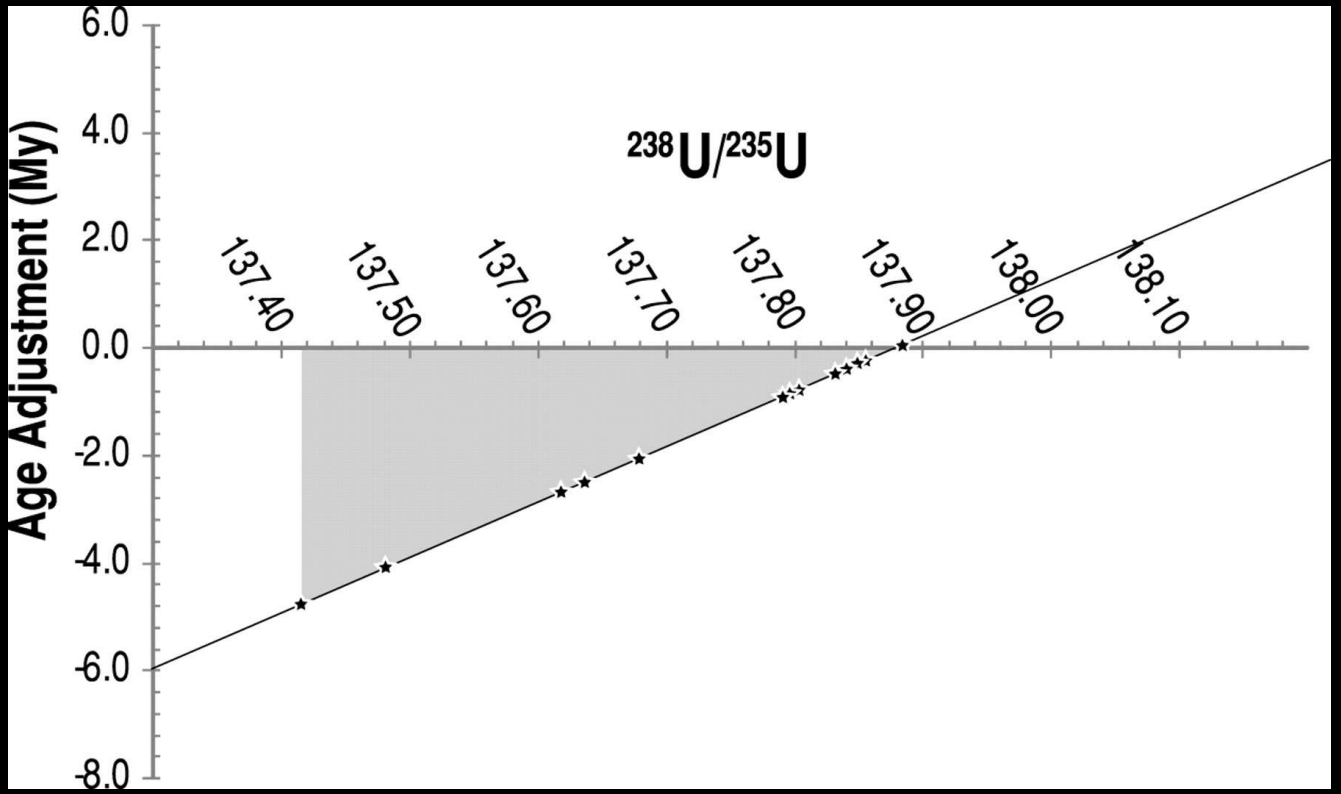
- U-Pb system has half-lives and systematics suitable for resolving events in the first 10 My of the solar system.
- The Pb-Pb age equation has been used to calculate the absolute ages of both meteorites and terrestrial materials.

$$\frac{\frac{^{207}\mathrm{Pb}}{^{204}\mathrm{Pb}} - \left(\frac{^{207}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_i}{\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}} - \left(\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_i} = \left(\frac{^{235}\mathrm{U}}{^{238}\mathrm{U}}\right)\left(\frac{e^{\lambda_5 t} - 1}{e^{\lambda_8 t} - 1}\right) = \frac{1}{137.88}\left(\frac{e^{\lambda_5 t} - 1}{e^{\lambda_8 t} - 1}\right)$$

- λ_5: the decay constant for ^{235}U to ^{207}Pb (half-lives, 0.704 By)
- λ_8: the decay constant for ^{238}U to ^{206}Pb (half-lives, 4.47 By)

- All Pb-Pb ages reported today are based on the fixed ^{238}U/ ^{235}U value.
- Any deviation of ^{238}U/ ^{235}U from 137.88 would cause miscalculation in the determined Pb-Pb age of a sample

Age adjustment required for samples



- ^{238}U/ ^{235}U variation results in 5My overestimation
- The largest overestimation occur in the CAIs experienced the largest Cm/U fractionation

Summary

- CAIs of the Allende meteorite display variable ^{238}U/ ^{235}U ratios
- The correlation of ^{238}U/ ^{235}U ratios with proxies for Cm/U provides strong evidence that the observed variations of ^{238}U/ ^{235}U in CAIs were produced by the decay of extant ^{247}Cm to ^{235}U in the early solar system.
- The variable ^{238}U/ ^{235}U ratios implies substantial uncertainties in the ages that were previously determined by Pb-Pb dating of CAIs, which may be overestimated by several million years.
- All future Pb-Pb studies must include ^{238}U/ ^{235}U ratios.