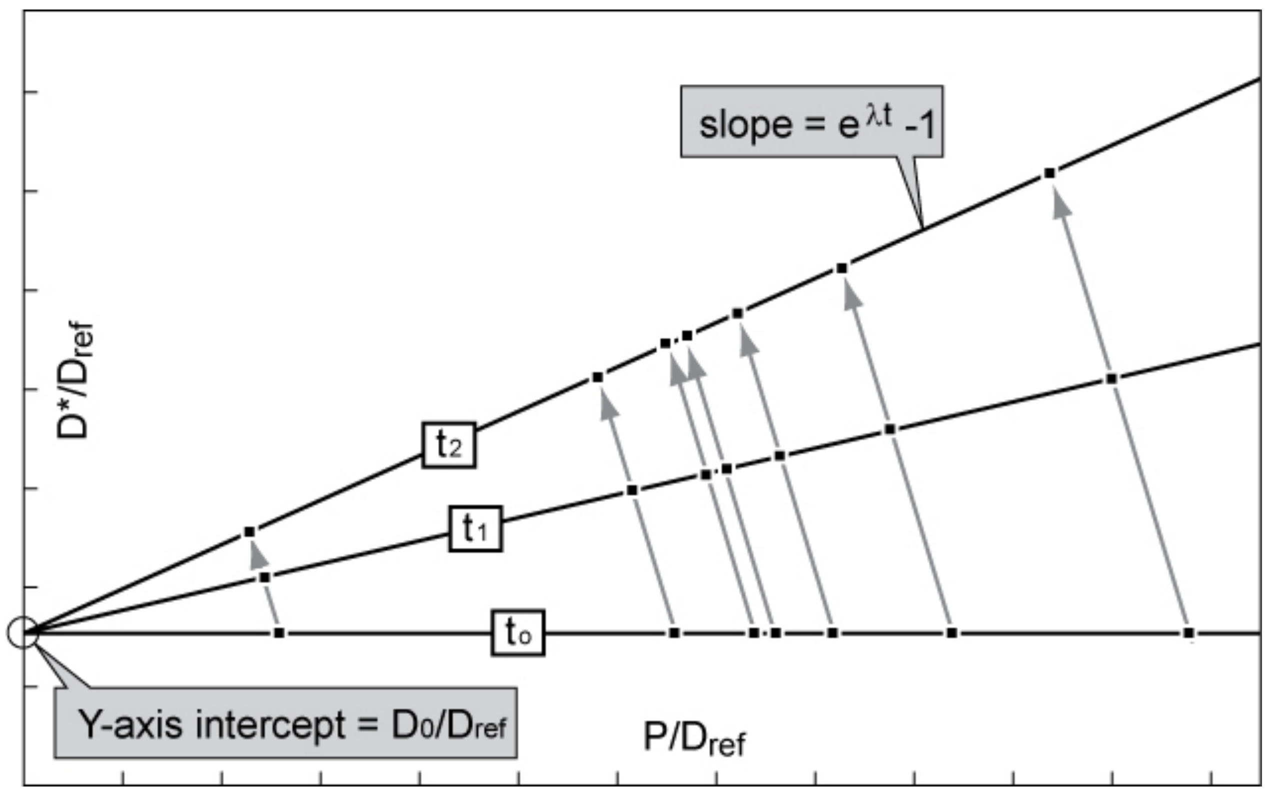
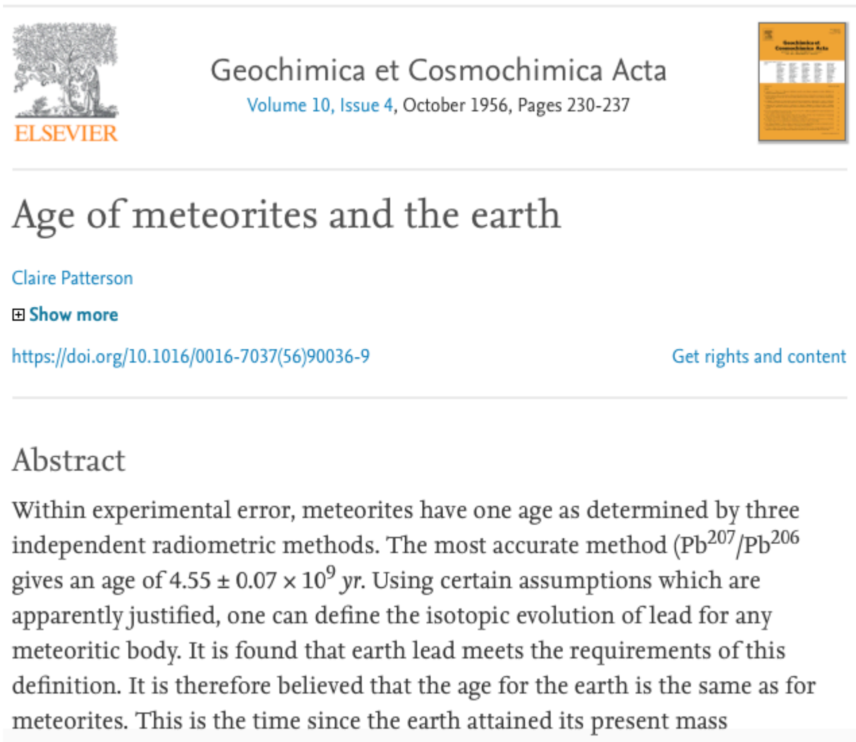
Radiogenic Dating



Pb-Pb dating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Geochimica et Cosmochimica Acta

Volume 10, Issue 4, October 1956, Pages 230-237

Age of meteorites and the earth

Claire Patterson

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Abstract

Within experimental error, meteorites have one age as determined by three independent radiometric methods. The most accurate method (Pb^{207}/Pb^{206}) gives an age of $4.55 \pm 0.07 \times 10^9$ yr. Using certain assumptions which are apparently justified, one can define the isotopic evolution of lead for any meteoritic body. It is found that earth lead meets the requirements of this definition. It is therefore believed that the age for the earth is the same as for meteorites. This is the time since the earth attained its present mass

Pb-Pb diagram

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Pb–Pb chronometry and the early Solar System

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Received 23 March 2016; accepted in revised form 27 October 2016; available online 4 November 2016

Abstract

Of the long-lived chronometric systems, only the dual decay of ^{238}U and ^{235}U to ^{206}Pb and ^{207}Pb, respectively, have appropriate half-lives to resolve the ages of meteorites and their components formed in the first 5 Myr of the Solar System. This paper reviews the theory and methods behind this chronometer, offers criteria to critically evaluate Pb–Pb ages and presents a summary of the current state and immediate future of the chronometry of the early Solar System. We recognize that there is some debate over the age of the Solar System, but conclude that an age of 4567.30 ± 0.16 Ma based on four CAIs dated individually by the same method in two different laboratories is presently the best constrained published value. We further conclude that nebular chondrules dated by the Pb–Pb method require that they formed contemporaneously with CAIs and continued to form for at least ~4 Myr, a conclusion that implies heterogeneous distribution of the short-lived ^{26}Al nuclide in the protoplanetary disk. Planetesimals were already forming by ~1 Myr after CAI formation, consistent with their growth predominantly through the accretion of chondrules. Nebular chondrule formation was completed by ~5 Myr after CAI formation when the impact-generated Cba chondrules formed after the disk was cleared of gas and dust. We note that the absolute age of the Solar System or any single early Solar System object is not fundamental to any significant scientific question and that it is important only to know the correct relative ages of objects being used to piece together the formation history of the Solar System. As such, we point out the risks inherent in comparing Pb–Pb ages produced by different approaches in different laboratories at the level of the internal errors of individual ages. Until a cross-calibration exercise using synthetic and natural standards establishes the reproducibility between laboratories, only ages from a single laboratory, or between laboratories having demonstrated concordance, can provide a reliable relative chronometric framework for the formation and evolution of the early Solar System.

Keywords: U-Pb chronology; Early Solar System; Meteorites; Calcium-aluminum inclusions; Chondrules

U-Pb Chronology of Chondrules

Connelly, J. N.; Bollard, J.; Bizzarro, M.

We present a summary and implications of our U-Pb chronometry of chondrules. We find that chondrules began forming contemporaneously with calcium aluminum inclusions and formed for 3.6 Myr.

Publication: Workshop on Chondrules and the Protoplanetary Disk, held February 27-28, 2017 in London, United Kingdom. LPI Contribution No. 1963, id.2025

Pub Date: February 2017

Bibcode: 2017LPICo1963.2025C

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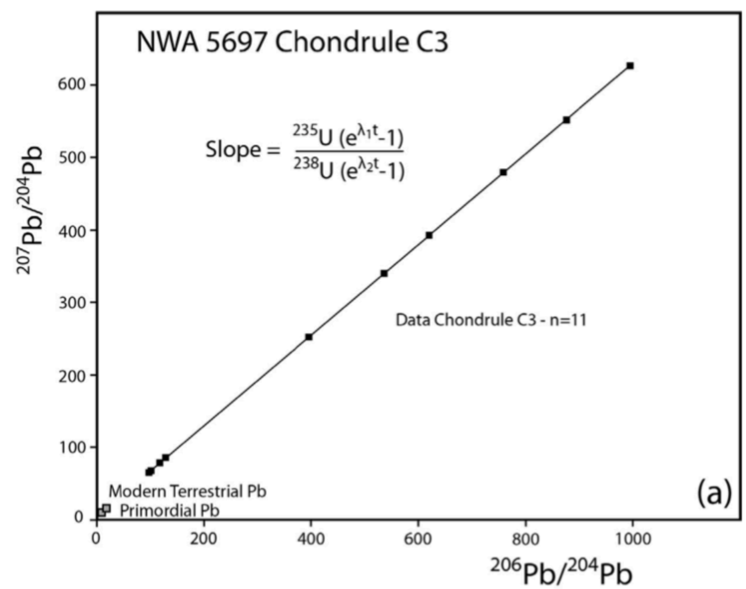

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Northwest Africa 5697

Basic information	**Name:** Northwest Africa 5697 This is an OFFICIAL meteorite name. **Abbreviation:** NWA 5697 **Observed fall:** No **Year found:** 2008 **Country:** (Northwest Africa) **Mass:** 547 g
Classification history:	Meteoritical Bulletin: MB 101 (2012) L3 **Recommended:** **L3** [explanation] This is 1 of 685 approved meteorites classified as L3. [show all] Search for other: L chondrites, L chondrites (type 3), Ordinary chondrites, and Ordinary chondrites (type 3)
Comments:	Approved 23 Aug 2012
Data from: MB101 Table 0 Line 0:	**Place of purchase:** Agadir, Morocco **Date:** P 2008 **Mass (g):** 547 **Pieces:** 1 **Class:** L3 **Shock stage:** S3 **Weathering grade:** W1 **Fayalite (mol%):** 22.1±8 (N=16) **Ferrosilite (mol%):** 17±6.8 (N=21) **Classifier:** A. Greshake, MNB **Type spec mass (g):** 22.6 **Type spec location:** MNB **Main mass:** Carsten Giessler **Comments:** The fresh meteorite contains abundant sharply defined chondrules with a mean diameter of ~700 um.; submitted by Ansgar Greshake
Institutions and collections	*MNB*: Museum für Naturkunde, Invalidenstraße 43, D-10115 Berlin, Germany (institutional address; updated 24 Dec 2011)

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Northwest Africa 5697 (L3)

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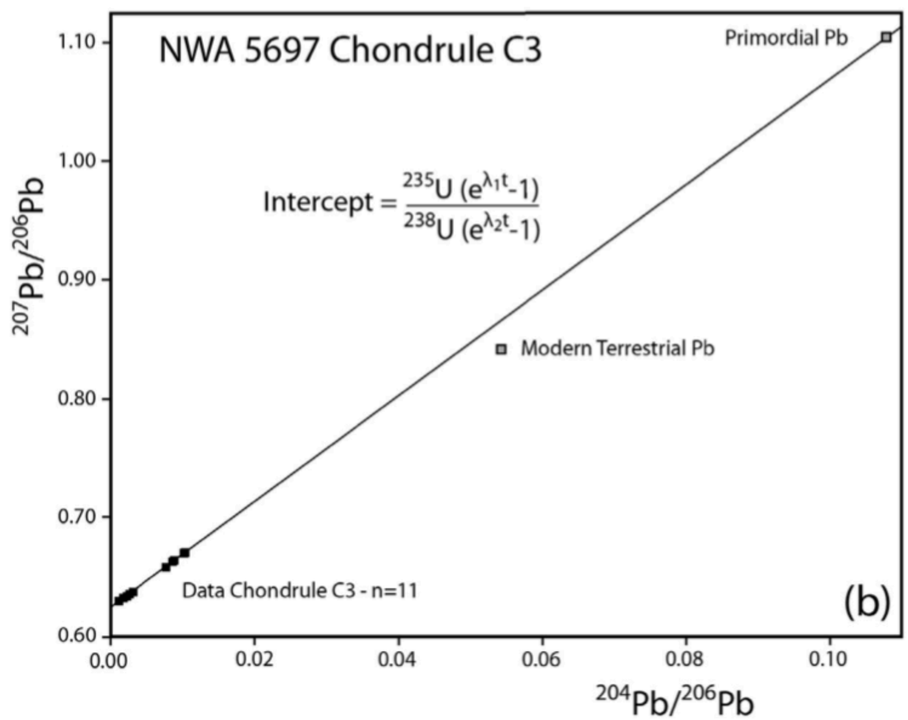
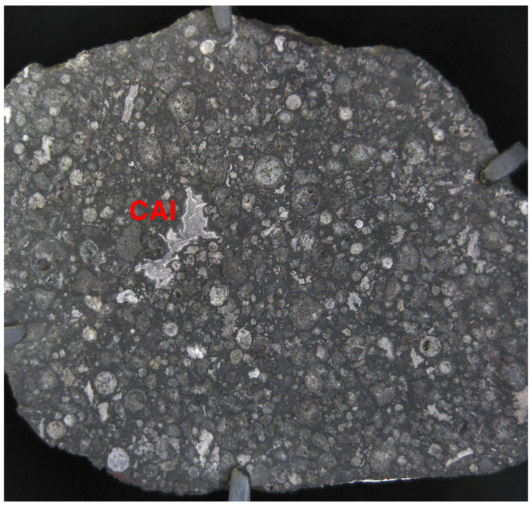
Inverse Pb-Pb diagram



Defining an age based on the $(^{207}Pb/^{206}Pb)_r$ ratio (otherwise known as a "Pb–Pb age") requires that any initial Pb incorporated into different phases had a single Pb isotopic composition, that the system remained closed and that the $^{238}U/^{235}U$ ratio is known for each individual sample (but not the U/Pb ratio). In some rare cases, the sample may not contain any initial Pb such that a pure $(^{207}Pb/^{206}Pb)_r$ component is directly measured. The widespread addition of tetraethyl-Pb to gasoline for over 50 years has contributed to the near ubiquitous contamination of terrestrial Pb in meteorites. As such, this third component of Pb in meteorites must be recognized and, most commonly, removed from the sample for meteoritic Pb isotopic measurements to provide accurate age information.

Chondrules vs CAIs



Chondrules

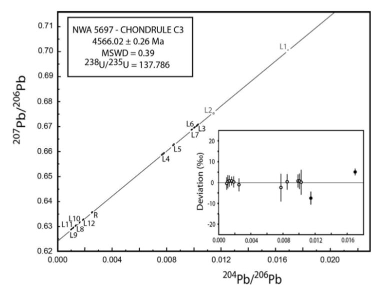


Fig. 5. Inverse Pb–Pb diagram for chondrule C3 from CV meteorite NWA 5697 reproduced from Connelly et al. (2012). Inset shows deviations of each analyses from the isochron in parts per thousand, with errors bars on each point corresponding to the total $^{207}Pb/^{206}Pb$ error of each analyses. Open symbols correspond to those fractions used in defining the isochron whereas black symbols were excluded in the regression. L = partial dissolution step; R = residue.

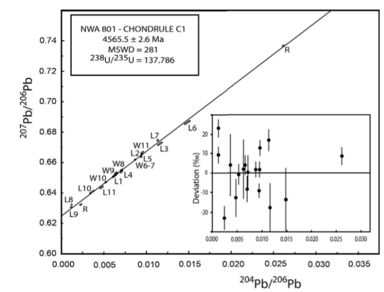


Fig. 6. Inverse Pb–Pb diagram for chondrule C1 from CR2 meteorite NWA 801 with a reference isochron line corresponding to an age of 4565.5 ± 2.6 Ma. Inset shows deviations of each analyses from the isochron in parts per thousand, with errors bars on each point corresponding to the total $^{207}Pb/^{206}Pb$ error of each analyses. L = partial dissolution step, W = wash step, R = residue.

CAI

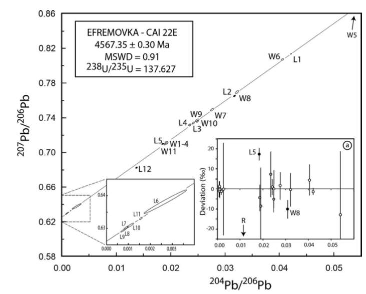
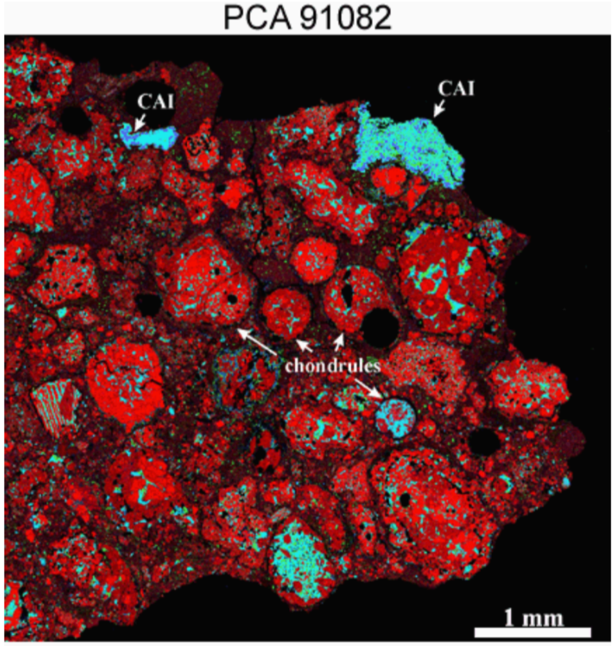


Fig. 7. Inverse Pb–Pb diagram for CAI 22E from CV meteorite Efremovka reproduced from Connelly et al. (2012). Inset (a) shows deviations of each analyses from the isochron in parts per thousand, with errors bars on each point corresponding to the total $^{207}Pb/^{206}Pb$ error of each analyses. Open symbols correspond to those fractions used to define the isochron, gray symbols overlap the isochron and black symbols do not overlap the isochrons (see text for discussion). W = wash step, L = partial dissolution step, R = residue.

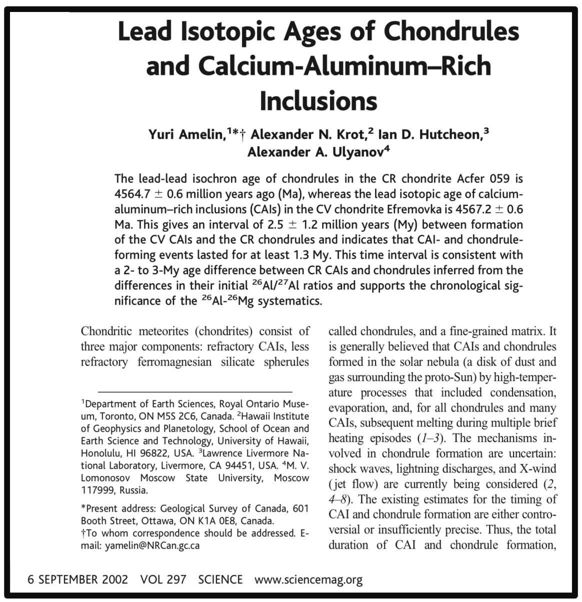
Calcium-Aluminum-rich Inclusions (CAIs)



(Alexander Krot, University of Hawaii)

This combined X-ray elemental map shows Mg (red), Ca (green) and Al (blue) of the CR carbonaceous chondrite PCA 91082. CAIs and chondrules are labeled. Rocks like these preserve a record of the processes and timing of events in the solar nebula.

Difference in Age



Lead Isotopic Ages of Chondrules and Calcium-Aluminum–Rich Inclusions

Yuri Amelin,[1*†] Alexander N. Krot,[2] Ian D. Hutcheon,[3] Alexander A. Ulyanov[4]

The lead-lead isochron age of chondrules in the CR chondrite Acfer 059 is 4564.7 ± 0.6 million years ago (Ma), whereas the lead isotopic age of calcium-aluminum–rich inclusions (CAIs) in the CV chondrite Efremovka is 4567.2 ± 0.6 Ma. This gives an interval of 2.5 ± 1.2 million years (My) between formation of the CV CAIs and the CR chondrules and indicates that CAI- and chondrule-forming events lasted for at least 1.3 My. This time interval is consistent with a 2- to 3-My age difference between CR CAIs and chondrules inferred from the differences in their initial $^{26}Al/^{27}Al$ ratios and supports the chronological significance of the ^{26}Al-^{26}Mg systematics.

Chondritic meteorites (chondrites) consist of three major components: refractory CAIs, less refractory ferromagnesian silicate spherules called chondrules, and a fine-grained matrix. It is generally believed that CAIs and chondrules formed in the solar nebula (a disk of dust and gas surrounding the proto-Sun) by high-temperature processes that included condensation, evaporation, and, for all chondrules and many CAIs, subsequent melting during multiple brief heating episodes (*1–3*). The mechanisms involved in chondrule formation are uncertain: shock waves, lightning discharges, and X-wind (jet flow) are currently being considered (*2*, *4–8*). The existing estimates for the timing of CAI and chondrule formation are either controversial or insufficiently precise. Thus, the total duration of CAI and chondrule formation,

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†To whom correspondence should be addressed. E-mail: yamelin@NRCan.gc.ca

6 SEPTEMBER 2002 VOL 297 SCIENCE www.sciencemag.org

CAIs are older than chondrules

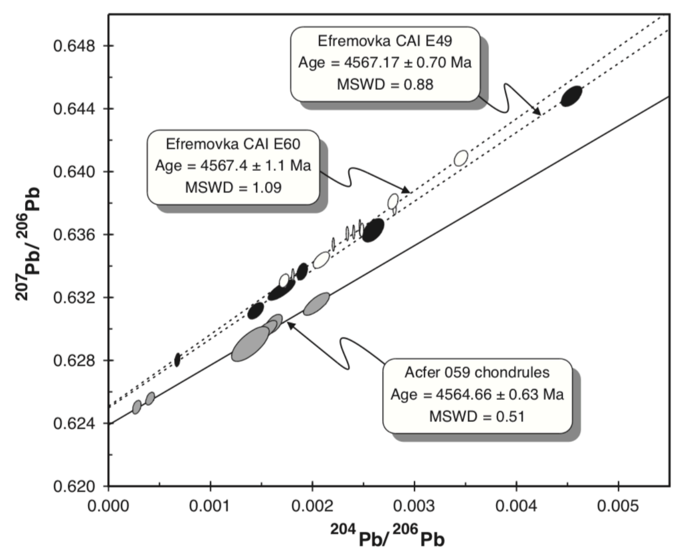
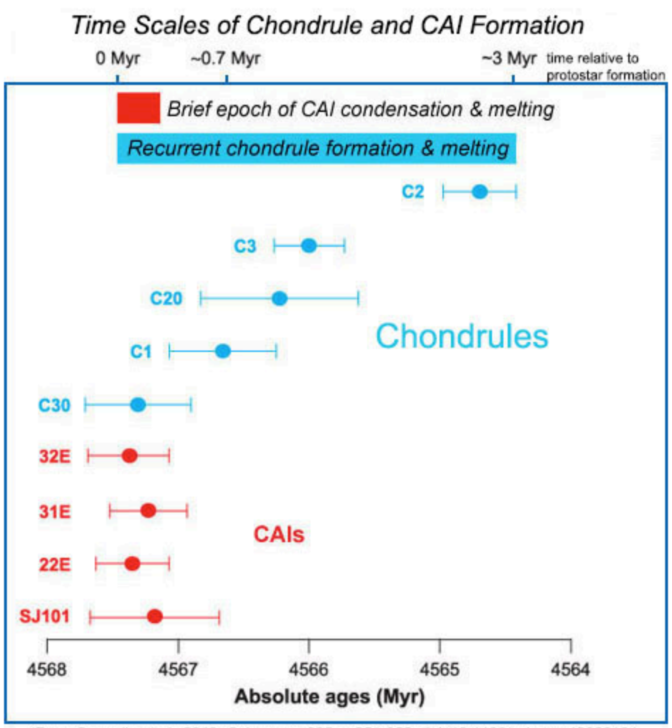


Fig. 1. Pb-Pb isochrons for the six most radiogenic Pb isotopic analyses of acid-washed chondrules from the CR chondrite Acfer 059 (solid line), and for acid-washed fractions from the Efremovka CAIs (dashed lines). $^{207}Pb/^{206}Pb$ ratios are not corrected for initial common Pb. Error ellipses are 2σ. Isochron age errors are 95% confidence intervals.

CAIs formed in a single episode
Chondrules formed for ~3 Myr after CAIs



(From Connelly *et al.*, 2012, *Science*, v. 338, p.651-655, doi: 10.1126/science.1226919.)

Calcium–Aluminum-Rich Inclusions in Chondritic Meteorites

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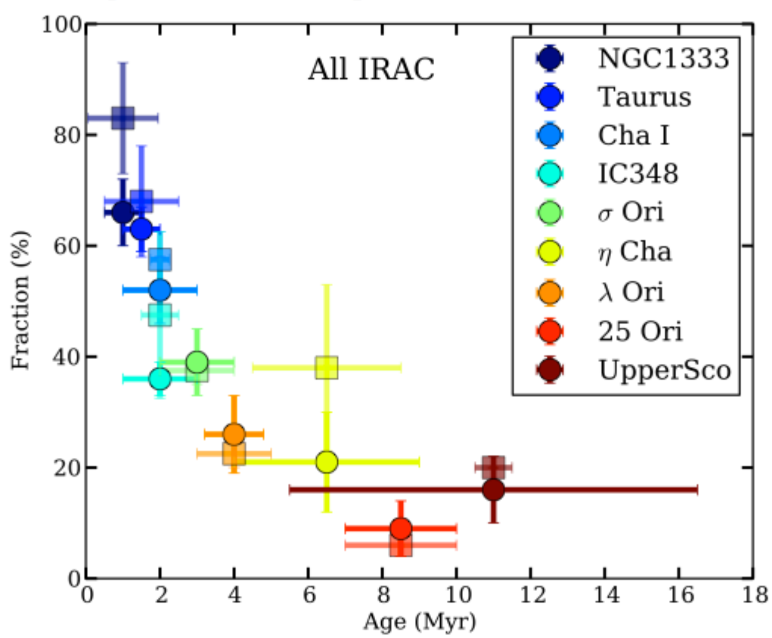
Smithsonian Institution, Washington, DC, USA

1.08.1 INTRODUCTION

Calcium–aluminum-rich inclusions (CAIs) are submillimeter- to centimeter-sized clasts in chondritic meteorites, whose ceramic-like chemistry and mineralogy set them apart from other chondrite components. Since their first descriptions more than 30 years ago (e.g., Christophe Michel-Lévy, 1968), they have been the objects of a vast amount of study. At first, interest centered on the close similarity of their mineralogy to the first phases predicted by thermodynamic calculations to condense out of a gas of solar composition during cooling from very high temperatures (e.g., Lord, 1965; Grossman, 1972). Immediately thereafter, CAIs were found to be extremely old (4.56 Ga) and to possess unusual isotopic compositions (in particular, in

Disk lifetime



(Ribas et al. 2014)

e-folding time ~2.5 Myr

Summary of Early Solar System evolution

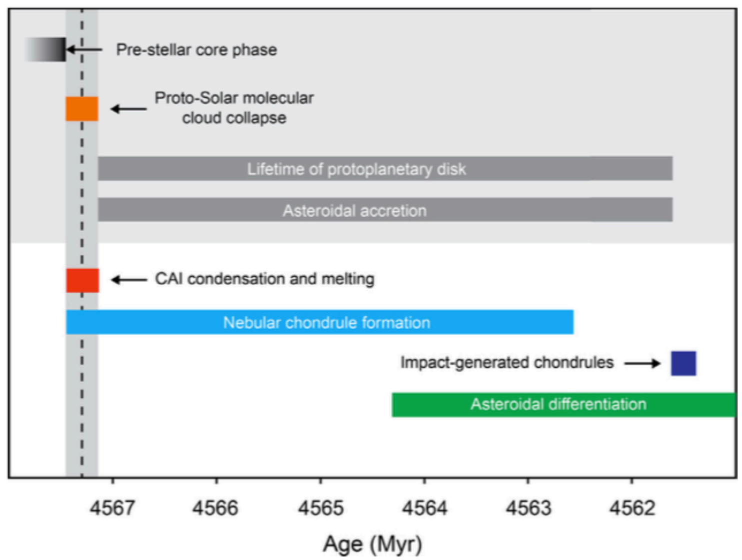


Fig. 9. Summary diagram of the chronology of the early Solar System based on Pb–Pb geochronology.