EVIDENCE FOR MULTIPLE SOURCES OF ^{10}BE IN THE EARLY SOLAR SYSTEM. D. Wielandt[1], K. Nagashima[2], A. N. Krot[1,2], G. R. Huss[2], M. A. Ivanova[3], and M. Bizzarro[1], [1]Centre for Star and Planet Formation, Øster Voldgade 5-7, 1350 København K, Denmark, wielandt@snm.ku.dk, [2]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, HI 96822, USA, [3]Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow 119991, Russia.

Introduction: With a half-life of 1.4 Myr, the decay of ^{10}Be to ^{10}B is considered a key indicator of late spallogenic contributions towards the nucleosynthetic make-up of the solar system, given that ^{10}Be is destroyed during stellar nucleosynthesis and formed near-exclusively by spallation reactions associated with cosmic rays [1]. Evidence for the former presence of ^{10}Be in meteorites has been inferred from the observation of a correlation between the excesses in ^{10}B and the beryllium abundance [e.g., 1–3] of minerals in calcium-aluminum-rich inclusions (CAIs), which are believed to be the earliest solids formed in our solar system. The range of solar system's initial ^{10}Be/^{9}Be ratio inferred from these studies is significantly higher than the expected contribution from the Galactic background of ~10^{-5}, requiring a late nucleosynthetic production or amplification of ^{10}Be prior to, or shortly after the formation of our solar system [1]. Several mechanisms have been suggested for this late enhancement of ^{10}Be, including magnetic focusing and enhanced trapping of Galactic Cosmic Rays (GCR) in the protosolar molecular cloud [4], ^{10}Be formation in an X-wind type setting through spallation of solar composition gas by solar cosmic rays [1], or *in situ* ^{10}Be formation or implantation through irradiation of the refractory inclusions or their precursor materials [e.g., 5, 6].

These scenarios can be tested by searching for non-chronometric variations in ^{10}Be/^{9}Be and cogenerated Li- and B-isotope anomalies among refractory inclusions that as a result of their varying petrogenesis may have preferentially sampled or recorded these reservoirs and processes. Therefore, we have performed high-precision Li-Be-B SIMS analysis of a suite of refractory inclusions from CV chondrites that contains both CAIs that formed with the canonical ^{26}Al/^{27}Al ratio of $(5.252\pm0.019)\times10^{-5}$ [7] (i.e., *canonical* CAIs) as well as the so-called FUN-CAIs (Fractionation and Unidentified Nuclear isotope anomalies) [8]. Canonical CAIs appear to have formed in a gas of approximately solar composition (gas/dust ratio of ~0.01 by mass) as condensates from vaporized nebular material and/or remelted condensates [9], possibly within the first 0.1 Myr of solar system formation [7, 10–12]. The canonical CV CAI-forming reservoir was apparently homogeneous with respect to ^{26}Al [7], oxygen [13], and other stable nuclides such as ^{50}Ti and ^{54}Cr [14, 15]. Therefore, these objects are samples of the homogenized refractory components of the gas, including its Be, and should not exhibit variable ^{10}Be/^{9}Be ratio unless ^{10}Be was locally synthesized in the gas or in the inclusions by exposure to particle irradiation from the proto-Sun. Whereas the majority of igneous canonical CAIs show small mass-dependent fractionation effects in Mg, Si, and O isotopes consistent with melting and evaporation during transient heating events at relatively high ambient pressure (from ~10^{-3} to ~10^{-5} bar), much larger mass-dependent fractionation effects are observed in FUN-CAIs, which appear to have experienced melt evaporation nearly in vacuum [16, 17]. The common presence of large mass-independent stable isotope anomalies of nucleosynthetic origin in FUN-CAIs [e.g., 8] indicate that their precursors escaped complete evaporation-recondensation in the solar nebula. Moreover, FUN-CAIs are also characterized by the absence or low initial abundance of ^{26}Al in their precursor material, suggesting that these objects represent evaporative residues of presolar aggregates that formed prior to the formation of canonical CAIs and the introduction and/or homogenization of ^{26}Al in the protoplanetary disk [18]. As such, FUN-CAIs may have retained the ^{10}Be abundance of the primordial dust inherited from the protosolar molecular cloud.

Table 1. Be-B systematics of CV CAIs measured.

CAI # (type)	^{10}Be/^{9}Be ×10^{-4}	^{10}B/^{11}B	MSWD
AXCAI 2771 (FUN CTA)	2.77±0.24	0.2519±0.0035	1.00
KT-1(FUN B)	3.37±0.20	0.2544±0.0031	1.09
31E (B)	4.71±0.80	0.2509±0.0026	1.05
E38 (B)	4.43±0.61	0.2539±0.0044	0.89
E48 (B)	4.82±0.25	0.2500±0.0020	1.00
E104 (CTA)	5.50±1.40	0.2427±0.0060	0.52
E104 (FTA)	6.70±0.86	0.2482±0.0006	1.12

Results: We measured Be-B-Li isotopes in four canonical CAIs (31E, E38, E48, and E104) from the reduced CV chondrite Efremovka as well as two FUN-CAIs (KT-1 and AXCAI 2771) from the oxidized CV chondrites NWA 779 and Axtell using the UH Cameca ims-1280. 31E, E38 and E48 are igneous Type B inclusions whereas 104E is a compound CAI composed of an coarse-grained igneous Compact Type A (CTA) domain as well as a finer-grained Fluffy Type A (FTA) domain. KT-1 is a Type B igneous CAI [19] wheareas AXCAI 2771 is a CTA [3]. We measured Li-Be-B isotopic compositions and concentrations with a combination of multicollection and peak jumping modes on the University of Hawai'i IMS 1280 SIMS. The ^{9}Be/^{11}B measurements were corrected with a sensitivity factor ~1.78 favouring Be, estimated from measurements on USGS basaltic glass standards.We note that diffences in Be/B sensitivity factor may have led to systematic differences in estimated $^{10}Be/^{9}Be$, as compared to other studies [i.e., 1–3]. The results of our measurements are summarized in Table 1. The AXCAI 2771 and KT-1 FUN-CAIs have the inferred $^{10}Be/^{9}Be$ ratios of $(2.77\pm0.24)\times10^{-4}$ and $(3.37\pm0.2)\times10^{-4}$, respectively, as well as superchondritic $^{10}B/^{11}B$ initial ratio. The canonical Type B CAIs 31E, E38 and E48 show similar initial $^{10}Be/^{9}Be$ ratios of ~$(4.4–4.8)\times10^{-4}$ that are identical within error, and significantly higher than those in the FUN CAIs. 31E and E38 have superchondritic $^{10}B/^{11}B$ initial ratio, while E48 has a superchondritic central value but is chondritic within error. The canonical compound Type A CAI E104 shows two internally consistent isochrones with essentially chondritic initial $^{10}B/^{11}B$ and $^{10}Be/^{9}Be$ of $(6.8\pm0.85)\times10^{-4}$ and $(5.6\pm1.39)\times10^{-4}$ for the FTA and CTA domains, respectively.

Discussion: Our measurements demonstrate the presence of at least four distinct fossil $^{10}Be/^{9}Be$ isochrons, lower in the FUN-CAIs than in the canonical CAIs, and variable within these classes. Although the variations in $^{10}Be/^{9}Be$ could, in principle, reflect differences in chronology or ongoing nucleosynthesis from a single source, our interpretation discounts chronology and favours the presence of multiple sources of ^{10}Be.

The observed > 10% variability in initial $^{10}Be/^{9}Be$ in canonical CAIs is discordant with high-precision ^{26}Al-^{26}Mg systematics, that suggest canonical CAIs or their precursors formed within a short timeframe compared to the ~1.4 Myr half-life of ^{10}Be [10], possibly as short as 4,000 years [7]. Similarly, the lower initial $^{10}Be/^{9}Be$ ratios recorded by the FUN-CAIs is difficult to reconcile with a late formation of these objects, as the $^{10}Be/^{9}Be$ should have decreased by an order of magnitude during the > 5 Myr of free decay required to reach the low or undetectable levels of ^{26}Al in FUN-CAIs, if these formed after canonical CAIs. Moreover late formation of FUN-CAIs also conflicts with their large and variable nucleosynthetic anomalies and ^{16}O-rich compositions, which are interpreted in the context of a formation near contemporaneously with or prior to canonical CAIs [18]. Therefore, we rule-out a strict chronological interpretation to explain the variability in initial $^{10}Be/^{9}Be$ present in canonical and FUN-CAIs.

The observed variations in the initial $^{10}Be/^{9}Be$ ratio among the canonical CAIs is a strong argument in favor of ongoing local gaseous or variable *in situ* production, as it is not clear how these inclusions could otherwise exhibit homogeneity with respect to ^{26}Al but not ^{10}Be. A near inescapable conclusion is also that the nucleosyntheses of ^{10}Be and ^{26}Al are decoupled. The distribution of the ^{10}B anomalies is in favor of *in situ* decay rather than *in situ* formation or implantation, as the MSWD are better in Be/B than in 1/B type regressions, indicating that the ^{10}B excesses most likely formed from ^{10}Be that was well mixed with ^{9}Be. This is also the case for the FTA E104 domain, which shows the highest $^{10}Be/^{9}Be$, and would have recorded the full amplitude of any *in situ* irradiation, suggesting that all canonical CAI largely inherited their ^{10}Be from the gas. The weak anticorrelation between $^{10}Be/^{9}Be$ and initial $^{10}B/^{11}B$ favors gaseous nucleosynthesis through spallation of CNO-nuclei, as *in situ* formation occurs exclusively through spallation of ^{16}O, which would tend to generate the opposite trend.

Gaseous ^{10}Be synthesis, however, fails to explain the presence of ^{10}Be in the two FUN-CAIs. The primary thermal processing of FUN-CAIs took place at low ambient pressures, and hence with minor interaction with solar gas. As such, the $^{10}Be/^{9}Be$ ratios recorded by the FUN-CAIs must reflect the ^{10}Be abundaces of the presolar dust inherited from the presolar molecular cloud. We note that the $^{10}Be/^{9}Be$ level of $\sim3\times10^{-4}$ is in overall agreement with the ^{10}Be abundance predicted to result from magnetic focusing and enhanced trapping of GCR in the presolar molecular cloud [4]. Therefore, we suggest that the $^{10}Be/^{9}Be$ level present in the FUN-CAIs represents a baseline level present in presolar material present in the cloud, generated via enhanced trapping of GCR. The higher and variable $^{10}Be/^{9}Be$ ratios present in the canonical CAIs reflects an additional ongoing ^{10}Be generation in the gaseous reservoir from which these inclusions formed.

However, the higher initial $^{10}Be/^{9}Be$ in KT-1 as compared to AXCAI 2771 is, in principle, inconsistent with a strict cloud capture scenario, as variations present in the parent cloud are efficiently homogenized during collapse to a disk. The simplest explanation for this high initial $^{10}Be/^{9}Be$ may be a higher level of *in situ* radiation in KT-1, consistent with anomalous common Li in this inclusion, or alternatively a > ∼150 Kyr formation interval between KT-1 and AXCAI 2771.

References: [1] McKeegan K. et al. (2001) *Science, 289,* 1334. [2] Sugiura N. et al. (2001) *MAPS, 36*, 1397. [3] Macpherson G. et al. (2003) *GCA, 67*, 3165. [4] Desch S. et al. (2004) *ApJ*, 602, 528. [5] Gounelle M. et al. (2001) *ApJ, 548,* 1051. [6] Bricker G. & Caffee M. (2010) *ApJ, 725,* 443. [7] Larsen K. et al. (2011) *ApJ, 753,* L37. [8] Wasserburg G. et al. (1977) *GRL, 4,* 299. [9] Grossman L. et al. (2000) *GCA, 64,* 2879. [10] Bizzarro M. et al. (2004) *Nature, 431,* 275. [11] Thrane K. et al. (2006) *ApJ, 646,* L159. [12] Jacobsen B. et al. (2008) *EPSL*, 272, 353. [13] Krot A. et al. (2010) *ApJ, 713,* 1159. [14] Trinquier A. et al. (2007) *ApJ, 655,* 1179. [15] Trinquier A. et al. (2009) *Science, 324,* 374. [16] Mendybaev R. et al. (2009) *LPSC, 40,* #2461. [17] Richter F. et al. (2007) *GCA, 71,* 5544. [18] Sahijpal S. & Goswami, J. N. (1998) *ApJ, 509,* L137. [19] Thrane K. et al. (2008) *ApJ, 680,* L141.