A NEW MODEL FOR THE ORIGIN OF TYPE-B CAIs. Alan E. Rubin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA (aerubin@ucla.edu).

Type-B CAIs are multi-mm- to multi-cm-size objects that differ from other CAI types in two principal respects: They are appreciably larger and occur only in CV chondrites. A new model for the origin of Type-B CAIs suggests that these characteristics are related.

Typical CAIs are surrounded by a Wark-Lovering (W-L) rim a few tens of µm in thickness that consists of a series of mono- or bi-mineralic layers of melilite, spinel and pyroxene along with hibonite and perovskite [1]. Accretionary rims (a form of igneous rim) surround the W-L rims [2]. The innermost layer contains abundant ^{16}O-rich forsterite [3]. Some accretionary rims in CV3 Allende contain Ca-pyroxene [2].

Chondrite groups have distinct chemical, isotopic and petrologic features and likely formed at different heliocentric distances. The properties of chondrules in different chondrite groups also vary; their O-isotopic compositions are distributed around that of the whole rock [4]. Chondrules appear to have formed locally.

The modal abundance of CAIs varies among chondrite groups (in vol.%): EH-EL, 0.01%; H-L-LL, 0.02%; R, 0.04%; CR, 0.6%; CV, 3.0%; CK, 4%; CM, 1.2%; CO, 1.0%; CI, 0% [5]. The highest abundances of CAIs occur among CV and CK chondrites. The CAI abundance in different regions of the nebula seems to have varied with heliocentric distance, peaking in the CV-CK region and declining farther out.

Fine-grained silicate matrix material is derived from nebular dust. The fraction of RP plus C chondrules anticorrelates with the abundance of matrix and, hence, with the inferred dust abundance in different nebular regions [6]. RP and C chondrules formed from total melts. Multiple melting of RP and C chondrules in the presence of abundant dust would facilitate the incorporation of dust particles into the droplets where they could serve as nuclei and cause crystallization of PP chondrules. (The survival of microchondrules in fine-grained rims around normal-size chondrules [7] indicates that neighboring dust can survive chondrule melting.) The fraction of RP and C chondrules would diminish in dusty nebular regions. In addition, chondrules that were remelted in dusty regions would tend to acquire thick igneous rims; more extensive remelting would lead to enveloping compound chondrules with thick secondary shells. Very extensive remelting would produce large unrimmed chondrules.

CV and CK chondrites have the largest chondrules, the fewest RP+C chondrules, the highest fraction of enveloping compound chondrules, the most chondrules with igneous rims, and the thickest igneous rims [6]. Nebular dust probably peaked in the CV-CK region.

Because CAI abundance peaks in this same region, it seems that CAIs were associated with nebular dust. This is consistent with the fact that matrix-rich chondrite groups have more CAIs than matrix-poor groups.

The association of CAIs and nebular dust may be due to aerodynamic forces that concentrated both types of objects in the same regions. Compact mm-size CAIs respond to aerodynamic drag the same way as highly porous, more massive, cm-size dustballs [5]. Remnants of such dustballs occur in chondrites as dark inclusions, matrix clumps, igneous rims on chondrules, and secondary shells on enveloping compound chondrules.

Although chondrules formed locally, it seems likely that the majority of CAIs did not. The similarities in O-isotopic composition of CAIs in ordinary, carbonaceous and enstatite chondrites imply that all of these objects were formed relatively near each other within the same O-isotopic reservoir [8]. That reservoir was probably close to the early Sun as indicated by the decay products of ^{10}Be ($t_{½}$ = 1.5 Ma) in some CAIs [9]. This short-lived radionuclide is produced only by nuclear spallation reactions resulting from intense radiation, not by stellar nucleosynthesis. (I assume that ^{10}Be in CAIs was not produced by galactic cosmic rays [10]). After CAIs formed near the Sun, they were transported through the nebula by aerodynamic forces.

Unlike other carbonaceous chondrites (in which Type-A CAIs are mm-size or smaller), CV chondrites contain some fluffy Type-A CAIs up to 2 cm in size [11]. These are compound objects consisting of melilite-rich nodules with W-L rims. The nodules were probably independent CAIs that were transported to the CV region where they collided and stuck together.

I suggest that, in contrast to other CAI types, Type-B CAIs formed directly in the CV region of the nebula by the clumping of type-A CAIs, the incorporation of significant amounts of mafic dust, and melting. (The components of chondrules were largely in the gas at this time.) During the heating events, Type-B CAIs experienced evaporation and became depleted in MgO and SiO_2 [12]. Type-B CAIs grew to large sizes for the same reason that CV-CK chondrules later became large – they were remelted (perhaps multiple times) after their precursor objects acquired appreciable amounts of dust. Because accretionary rims around CAIs contain abundant forsterite [3], the local dust was probably forsterite-rich. (This model resembles that of [13] who suggested that Type-B CAIs formed from altered Type-A objects after acquiring olivine.)

Mass-balance calculations (wt.%) using published CAI bulk compositions [14,15] show that a mixture of

87% mean Type-A CAIs [22.8% SiO_2, 34.7% Al_2O_3, 5.5% MgO, 36.8% CaO] and 13% forsterite [42.7% SiO_2, 57.3% MgO] yields a composition [25.4% SiO_2, 30.2% Al_2O_3, 12.3% MgO, 32.1% CaO] similar to that of mean Type-B CAIs [28.6% SiO_2, 32.3% Al_2O_3, 11.4% MgO, 27.6% CaO]. If greater amounts of forsterite were incorporated into clumped Type-A CAIs prior to melting, a cm-size forsterite-bearing Type-B CAI could have formed. A mixture of 76% of a particular compact Type-A CAI from CV3 Leoville [32.1% SiO_2, 23.6% Al_2O_3, 5.5% MgO, 38.8% CaO] and 24% forsterite would yield a composition [34.7% SiO_2, 18.0% Al_2O_3, 17.9% MgO, 29.4% CaO] similar to that of a particular forsterite-bearing Type-B CAI from CV3 Efremovka [39.2% SiO_2, 18.5% Al_2O_3, 16.8% MgO, 24.7% CaO]. Addition of forsterite and Ca-pyroxene to a Type-A CAI can approximate the positions of Type-B CAIs [11] on the plane Al_2O_3-Mg_2SiO_4-Ca_2SiO_4 projected from spinel ($MgAl_2O_4$).

If substantial evaporation of MgO and SiO_2 occurred during the heating of Type-B CAI precursors, then the mass-balance calculations are lower limits on the amount of forsterite that was added to clumped Type-A CAIs to produce Type-B compositions.

There is geochemical support for this model: (1) The compositions of Type-B CAIs are less refractory than Type A [11] because mafic dust was incorporated into Type-B precursors. (2) Type-B CAIs show more evidence than fluffy Type-As of a late disturbance in the ^{26}Al-^{26}Mg and ^{10}Be-^{10}B systematics [16,17]. This is due to clumps of Type-A CAIs having acquired mafic dust and experiencing remelting. (3) The W-L rims on Type-A and Type-B CAIs within a single meteorite are systematically different even though the inclusions may have underlying gehlenite layers of nearly identical composition [1]. One of the characteristic W-L layers around Type-B (but not Type-A) CAIs is forsterite [1], indicating that Type-A and Type-B CAIs acquired their W-L rims in different nebular settings.

If the small amount of Na in melilite in Type-B CAIs [18] is primary (and not due to parent-body aqueous alteration), it may have been derived (along with forsterite) from nebular dust. This would imply that Type-B CAIs experienced their final melting event after ambient temperatures had cooled below the condensation temperature of Na (~960 K). Type-A CAIs would have formed at higher temperatures at an earlier time in a different nebular region.

Melting and partial evaporation of the precursors of Type-B CAIs could have been caused by shock waves [19] in the CV-CK region of the nebula that heated these objects to temperatures of 1250-1450ºC [12,15].

CAIs appear to be 1-2 Ma older than chondrules [20,21] and may have been prevented from drifting into the Sun prior to accretion by nebular turbulence [22]. During the period between CAI and chondrule formation, the shock waves that melted the Type-B CAIs could have dissipated. Chondrules were produced later by local flash heating (as indicated by their inferred rapid cooling rates [23], the nonspherical shapes of many chondrules [24], and the presence of microchondrule-bearing fine-grained rims around some normal-size chondrules [7]). The different heating mechanisms of CAIs and chondrules can account for the mass-fractionation associated with Type-B CAIs and its absence in (quickly cooled) chondrules.

As the nebula cooled, more-oxidized materials condensed. Parcels of gas and dust with distinct O-isotopic compositions may have fallen into the nebula from the surrounding molecular cloud [25]. Existing dustballs incorporated and reacted with this material and became more ferroan and depleted in ^{16}O. Chondrules were produced throughout this period, type-I chondrules forming prior to type-II chondrules.

The paucity of compound chondrule-CAI objects might be due to CAIs settling to the nebular midplane before chondrule formation. Chondrules may have formed at the interface between the dusty midplane and a gas-rich zone above it [26]. Chondrite accretion occurred after chondrules also settled to the midplane.

References: [1] Wark D. A. and Lovering J. F. (1977) *PLSC, 8*, 95-112. [2] MacPherson G. J. et al. (1985) *GCA, 49*, 2267-2279. [3] Cosarinsky M. et al. (2002) *MPS, 37*, A38. [4] Rubin A. E. (2000) *Earth Sci. Rev*., *50*, 3-27. [5] Rubin A. E. (2011) *Icarus*, submitted. [6] Rubin A. E. (2010) *GCA*, *74*, 4807-4828. [7] Krot A. N. et al. (1997) *GCA*, *61*, 463-473. [8] Guan Y. et al. (2000) *EPSL*, *181*, 271-277. [9] McKeegan K. D. et al. (2000) *Science*, *289*, 1334-1337. [10] Desch S. J. et al. *Ap. J.*, *602*,528-542. [11] MacPherson G. J. (2005) In *Meteorites, Comets, and Planets*, 201-246. [12] Richter F. M. (2006) *MPS, 41*, 83-93. [13] MacPherson G. J. and Huss G. R. (2000) *LPS, 31*, abst.1796. [14] Grossman L. et al. (2000) *GCA*, *64*, 2879-2894. [15] Grossman L. et al. (2008) *GCA*, *72*, 3001-3021. [16] MacPherson G. J. et al. (1995) *Meteoritics*, *30*, 365-386. [17] MacPherson G. J. et al. (2003) *GCA*, *67*, 3165-3179. [18] MacPherson G. J. and Davis A. M. (1993*) GCA, 57*, 231-243. [19] Desch S. J. and Connolly H. C. (2002) *MPS, 37*, 183-207. [20] Mostefaoui S. et al. (2001) *MPS*, *37*, 421-438. [21] Amelin Y. et al. (2002) *Science, 297*, 1678-1683. [22] Cuzzi J. N. et al. (2003*) Icarus, 166*, 385-402. [23] Wasson J. T. (1996) In *Chondrules and the Protoplanetary Disk,* 45-54. [24] Rubin A. E. and Wasson J. T. (2005) *GCA*, *69*, 211-220. [25] Wasson J. T. (2000) *Rev. Geophys., 38,* 491-512. [26] Wasson J. T. and Rasmussen K. L. (1984) *LPS*, *15*, 896-897.