TYPE-IAB CHONDRULES IN LL3.0 SEMARKONA: NO NEED FOR HIGH PARTIAL PRESSURES OF SiO$_2$ IN THE SOLAR NEBULA. Alan E. Rubin, Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA. (arubin@ucla.edu).

**Introduction:** High partial pressures of SiO$_2$ in the solar nebula have been invoked to explain the apparent enrichment of low-Ca pyroxene relative to olivine at the peripheries of low-FeO (Type-IAB) porphyritic olivine-pyroxene chondrules in different chondrite groups: (1) Chaussidon et al. [1] found that olivine is richer in $^{16}$O than low-Ca pyroxene in Type-IAB CV and CR chondrules and postulated that one-third of the oxygen in the low-Ca pyroxene was introduced by nebular SiO$_2$. (2) Tissandier et al. [2] conducted isothermal condensation experiments wherein partially molten synthetic samples were exposed to elevated SiO$_2$ partial pressures; they found that the resulting textures resembled those of natural chondrules in LL3.0 Semarkona. (3) Harju et al. [3,4] observed differences in $^{29}$Si between olivine and low-Ca pyroxene in one CV3 Type-IAB chondrule and one CR2.8 Type-IAB chondrule and concluded that, in these two cases, the fractionation was caused by Si isotopic condensation in the nebula under near-equilibrium conditions.

There are potential problems with postulating high gas pressures in the nebula. Such models require heating of substantial regions of the nebula [5] and evaporation of large amounts of dust [6].

1. Enormous amounts of energy are necessary to melt chondrules, evaporate ambient fines and heat the surrounding gas. The energy must be discharged rapidly, probably within minutes to hours [7]. Viable heat sources are problematic (although Tissandier et al. [2] speculated that variable and intense radiation emanating from the nascent Sun could be responsible).

2. Relict mafic silicate grains would dissolve in chondrule melts at prolonged elevated temperatures within short periods of time. A 2-mm-diameter grain of enstatite would melt completely at 1870 K in 0.12 s; likewise, forsterite would melt quickly at 2170 K [8]. Soulié et al. [9] found that, at 1720 – 1810 K, forsterite would dissolve quickly in chondrule-composition melts; their experimentally determined dissolution rates range from 5 $\mu$m min$^{-1}$ to 22 $\mu$m min$^{-1}$. These results, coupled with the common occurrence of relict grains in chondrules [10], indicate that typical chondrules could not have remained at elevated temperatures for more than a few seconds [8]. Similarly, olivine nuclei in chondrule melts would have melted or evaporated, hampering the subsequent development of porphyritic chondrule textures [11].

3. In any gaseous environment with a uniform temperature, small molten objects (with high surface-area/volume ratios) would cool faster and solidify sooner than larger molten objects. In megameter-scale environments in which all droplets are hot for extended periods, adhering compound chondrules should generally consist of a large molten object and a small solid one. Most often, the opposite is the case [12].

4. Igneous rims surround ~10% of OC chondrules and ~50% of CV chondrules [13]. These rims contain glass, zoned mafic silicate grains and abundant troilite. Under relatively high p(H$_2$) conditions (as inferred for the nebula), H$_2$S would evaporate from troilite at moderate temperatures (~1070-1240 K), leaving residual metallic Fe [14]; this is inconsistent with the abundant troilite in igneous rims. It is difficult to envision how igneous rims could have formed in large, hot regions of the nebula; they more likely formed by flash-melting porous, fine-grained rims around solid chondrules.

I offer an alternative model for forming Type-IAB chondrules that does not require high partial pressures of SiO$_2$ in the solar nebula. The model is based on my observations of Type-IAB and Type-IB chondrules in LL3.0 Semarkona (Fig. 1).

**Results and Discussion:** Tissandier et al. [2] modeled Type-IAB chondrules as having formed from Type-IA (low-FeO porphyritic olivine) chondrules by reaction of olivine with nebular SiO$_2$ while chondrules were partly molten. But it does not seem likely that Type-IAB chondrules initially were Type-IA. Many Type-IAB chondrules have high pyroxene/olivine modal ratios. I surveyed Type-IAB and Type-IB chondrules in two thin sections of Semarkona and found a continuum between the two types; I arbitrarily assign the boundary at 20 vol.% olivine. My estimates of the three-dimensional structures indicate that Type-IAB chondrules typically consist of (in vol.%) 45-65% low-Ca pyroxene, 20-30% olivine, 15-35% mesostasis and 1-5% metallic Fe-Ni. It is useful to think of Type-IAB chondrules as Type-IB (low-FeO porphyritic pyroxene) chondrules containing ≥20 vol.% relict olivine.

It is reasonable to assume that, at a particular epoch in nebular history, dust aggregates would be forsterite rich. Appreciable melting of these aggregates would produce olivine-rich chondrules; if sufficient numbers of nuclei were present during crystallization, Type-IA chondrules would form. Collisions among Type-IA chondrules would dislodge olivine phenocrysts and phenocryst fragments which could subsequently be incorporated into chondrules as relict grains.
As ambient temperatures cooled, forsterite reacted with nebular gas to form enstatite. At the end of this epoch, many of the fine-grained dust aggregates in the nebula would have tended to be enstatite rich. Some aggregates would have contained coarse relict olivine grains from previously disrupted Type-I chondrules.

At some point many enstatite-rich aggregates were melted sufficiently (perhaps ~40%) for them to develop a spheroidal shape due to surface tension and form pyroxene-rich chondrules. The surface of the droplets radiated heat into free space and cooled faster than the interior. Low-Ca pyroxene was the liquids phase. I suggest that elongated crystals of low-Ca pyroxene crystallized at the surface, perhaps forming a discontinuous spherical shell roughly analogous to the more-complete shells that surround many barred olivine chondrules. Relict olivine and low-Ca pyroxene grains were scattered throughout the chondrule. Multiple heating events [15] caused all the low-Ca pyroxene grains (at the surface and in the interior) to grow at the expense of surrounding mesostasis (most of which was probably interconnected). As the low-Ca pyroxene grains at the surface coarsened, they surrounded some relict olivine grains in their vicinity, forming poikilitic textures. The growing low-Ca pyroxene grains abutted other relict olivines and grew alongside and around them. Some mesostasis remained at or near the surface; some patches of mesostasis were surrounded by low-Ca pyroxene and formed melt pockets. (The relict olivine grains lack melt pockets.) The other major components of the chondrule (relict olivine grains, other pyroxene grains and additional mesostasis) remained beneath the surface, closer to the chondrule center. This process produced a Type-I chondrule texture (Fig. 1).

An implicit prediction of this model is that the low-Ca pyroxene grains at the surface of Type-I chondrules are normally zoned. However, Jones [16] found little evidence of compositional zoning in Semarkona Type-I and Type-IB chondrules. I made a series of parallel traces with the UCLA electron microprobe across three low-Ca pyroxene grains at the periphery of a Type-I chondrule (H40) in Semarkona section AMNH 4128-2 (Fig. 1). In going from the grain core to the grain edge facing the chondrule interior, the data are generally consistent with normal zoning: MgO decreases (by ~2%), Al₂O₃ increases (by ~80%), CaO increases (by ~80%), Cr₂O₃ increases (by ~30%), and MnO increases (by ~400%). However, FeO is essentially unchanged, inconsistent with normal zoning. This indicates that, if the low-Ca pyroxene grains formed by fractional crystallization, the Fe distribution coefficient between mineral and melt was near unity. I suggest that this was caused by minor reduction of FeO in the mesostasis during melting and addition of the reduced Fe to metallic Fe-Ni blebs. This is consistent with reduction commonly occurring during chondrule melting, evident in “dusty” relict olivine grains [17,18].

**Conclusions:** In chondrule-formation models involving multiple melting and rapid cooling at canonical nebular gas pressures, there is (1) less melting and evaporation of critical nuclei in chondrule melts (thereby facilitating the common development of porphyritic textures), (2) less destruction of relict grains, (3) less volatile loss, and (4) a lower likelihood of K-isotopic fractionation. Type-I chondrules probably formed by such processes and there is no need to postulate high total gas pressures or high partial pressures of lithophile elements in the solar nebula [6,19].

**References:**

![Fig. 1. Type-I chondrule H40 from Semarkona (LL3.0). Low-Ca pyroxene (px) grains (medium gray) near the periphery surround or abut relict olivine (ol) grains (dark gray). Also present are Ca-pyroxene (very light gray), abundant glassy mesostasis (light gray) and blebs of metallic Fe-Ni (white).](image-url)