# CB CHONDRITES COULD HAVE FORMED IN AN IMPACT PLUME.

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**Introduction:** Petaev *et al.* [1] proposed that zoned metal grains in the $CB_b$ chondrite QUE 94411 (hereafter QUE) condensed at a total pressure ($P^{tot}$) of $10^{-4}$ bar from a solar nebular region enriched in dust of ~CI composition by a factor of 10-40 relative to solar abundances. Krot *et al.* [2] noted that skeletal olivine (SO) and cryptocrystalline (CC) chondrules in QUE and Hammadah al Hamra 237 (HH) are low in FeO (1-4 wt%) and Na-free. Because SO are higher in refractory lithophiles than CC, both chondrule types contain no metal inclusions and metal contains inclusions with similar compositions to CCs, they suggested that SO chondrules condensed at a higher T than CC chondrules, and that both types condensed at a higher T than the metal, all at conditions inferred in [1] and earlier than the formation of most chondrites. Campbell *et al.* [3] found that the Ir/Fe, Pd/Fe and Ni/Fe ratios in unzoned metal grains in the $CB_a$ chondrites Bencubbin, Weatherford and Gujba are consistent with their having condensed from a gas whose partial pressures of siderophiles were $10^7$x higher than in a gas of solar composition at $P^{tot}=10^{-4}$ bar, and suggested that both the metal and the low-FeO, barred olivine (BO) and CC chondrules in the $CB_a$s condensed from a plume generated by a protoplanetary impact involving a metal-rich body and one containing low-FeO silicates. Krot *et al.* [4] used $^{207}Pb$-$^{206}Pb$ dating to show that HH chondrules and SO chondrules from Gujba formed contemporaneously ~5 my after CAI condensation, and suggested that the components of both $CB_a$ and $CB_b$ chondrites formed in a giant impact, SO chondrules and unzoned metal in Gujba by melting, CC chondrules in HH by gas-liquid condensation and zoned metal grains in HH by gas-solid condensation. Such a model does not take into account the finding of negative and positive Fe isotopic mass-fractionations in Gujba metal and chondrules, resp. [5], suggesting that the unzoned metal is a quickly-formed condensate that formed before the Gujba chondrules, nor the unique siderophile element contents of that metal. Thus, at one time or another, a condensation origin has been ascribed to each of these components, albeit over a wide range of conditions, and it has been proposed that all of them formed in a protoplanetary impact. Therefore, we set out to see if a common set of conditions could explain the origin of all these components, and if the conditions require an origin in an impact plume.

**Technique:** First, the VAPORS program [6] was used to calculate the equilibrium compositions of silicates that co-condense with metal, and the bulk Fe, Ni, Co and Cr contents of that metal as a function of T under the conditions proposed in [1]. Pd and Ir contents of the metal were then calculated using the same vapor pressure and activity coefficient data as in [7]. Then, the impact plume model of [3] was tested. Due to the genetic relationship of CBs to CR chondrites [8], the metallic body was assumed to have been the core of a tidally disrupted body with the composition of CR metal [9], and the silicate body an H chondrite [10]. The metal/silicate ratio of CBs was assumed to be representative of the plume, requiring it to be composed of 2.8 gm CR metal/gm H chondrite. Residual nebular gas was assumed to be complementary to H chondrite, so the dust enrichment is 9.6x larger for siderophiles than for lithophiles, relative to solar composition. As above, VAPORS [6] was used to calculate equilibrium compositions of silicates and metal as a function of T at various combinations of dust enrichment and $P^{tot}$.

**Results:** Calculated compositions of bulk silicates are compared with those of SO and CC chondrules [2] in Fig. 1. Bulk chemical compositions of QUE metal grains were calculated from traverses [7] and plotted with those of unzoned metal grains [3] in Figs. 2 and 3, along with computed metal grain compositions. One zoned and one unzoned QUE grain from [7] plot within the trends for unzoned grains from $CB_a$s [3]. At the low end of the range of dust enrichments, 10x, proposed by Petaev *et al.* [1] for zoned metal grain formation, there is no field of silicate liquid stability. At the upper end, 50x, silicate condensates are only partially molten. When their bulk $CaO+Al_2O_3$ contents are like those of SO chondrules, their $SiO_2$ and FeO contents are much lower than in those objects (45-52 and 2.2-2.9 wt%, resp.). Silicate condensate composition trends do intersect the field of CC chondrules at the upper end of their range of $CaO+Al_2O_3$ but at an FeO content (0.77 wt%) at the low end of those for CCs (0.7-2.5 wt%). On each of Figs. 2 and 3, the family of curves for the 10-50x range of CI dust enrichments passes between the compositions of zoned metal grains, but is compatible with only one of them. They intersect the composition trends of the unzoned grains at the lower ends of the ranges of Pd/Fe and Ir/Fe ratios; to reach the highest Pd/Fe ratios among the unzoned grains requires much higher siderophile partial pressures, as seen by [3]. It is noted that the modest $P^{tot}$ and dust enrichment of [1] are possible solar nebular conditions not requiring an impact plume for their production. For the plume model involving an impact between a CR metal body and an H chondritic body, computed paths of silicate compositions do not match bulk compositions of SO chondrules but, for silicate dust enrichments of 600-1500x, FeO contents (0.8-2.2 wt%) are like those of CC chondrules where the paths intersect the CC chondrule trend (Fig. 1). At these silicate dust enrichments, calculated composition paths of metal condensates at $P^{tot}=10^{-2}$-$10^{-3}$ bar are very good matches to the bulk compositions of unzoned grains from $CB_a$s in Figs. 2 and 3. Model curves at $P^{tot}=10^{-5}$-$10^{-8}$ bar give good matches to Pd contents of many zoned metal grains from QUE and of those unzoned grains with relatively low Pd contents (Fig. 2), but plot at higher Ir contents than half the zoned grains (Fig. 3). A wide range of bulk Cr contents is observed at a given Ni content in both kinds of metal grains. Predicted Cr contents are in good agreement with those of many grains with high Cr/Ni ratios but 30-50% below those of many high-Ni unzoned grains.

**Conclusions:** In this model, an impact between a CR metal body and an H chondrite body is assumed to produce a plume with the same metal/silicate ratio as a CB chondrite and a silicate dust/gas ratio of 600-1500 relative to solar composition. Equilibrium condensation from such a plume would yield the arrays of Pd/Fe and Ir/Fe *vs* Ni/Fe ratios reported for bulk compositions of metal grains in CB chondrites, most unzoned grains at $10^{-2}$-$10^{-3}$ bar, where liquid metal condenses; and most zoned grains at $10^{-5}$-$10^{-8}$ bar, where solid metal condenses. Both grain types could have formed in the same impact plume if it were heterogeneous in $P^{tot}$. Though the assumed dust enrichments would stabilize the FeO contents of CC chondrules, very few CB chondrules have bulk compositions lying along equilibrium condensation trends. They may have formed by melting of silicate mixtures. To stabilize FeO contents of SO chondrules, slightly higher silicate dust enrichments are needed; they would have to be offset by lower $P^{tot}$ to yield identical fits in Figs. 2 and 3.

**References:** [1] Petaev M. I. *et al.* (2001) *MAPS*, *36*, 93-106. [2] Krot A. N. *et al.* (2001) *Science*, *291*, 1776-1779. [3] Campbell A. J. *et al.* (2002) *GCA*, *66*, 647-660. [4] Krot A. N. *et al.* (2005) *Nature*, *436*, 989-992. [5] Tang H. and Dauphas N. (2012) *EPSL*, *359-360*, 248-263. [6] Ebel D. S. & Grossman L. (2000) *GCA*, *64*, 339-366. [7] Campbell A. J. *et al.* (2001) *GCA*, *65*, 163-180. [8] Weisberg M. K. *et al.* (2001) *MAPS*, *36*, 401-418. [9] Kong P. *et al.* (1999) *GCA*, *63*, 2637-3652. [10] Jarosewich E. (1990) *Meteoritics*, *25*, 323-337.

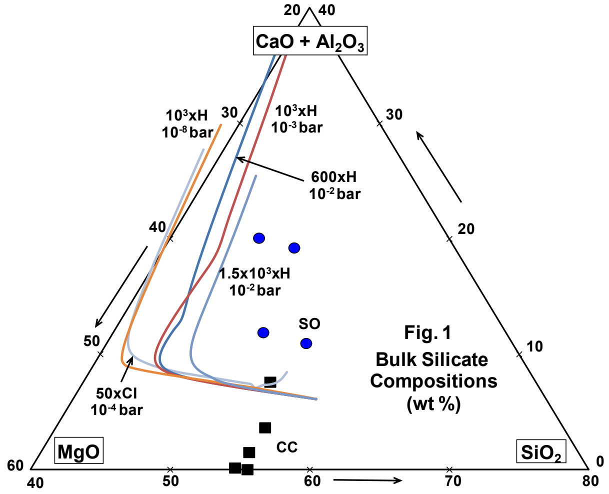

Fig. 1 Bulk Silicate Compositions (wt %)

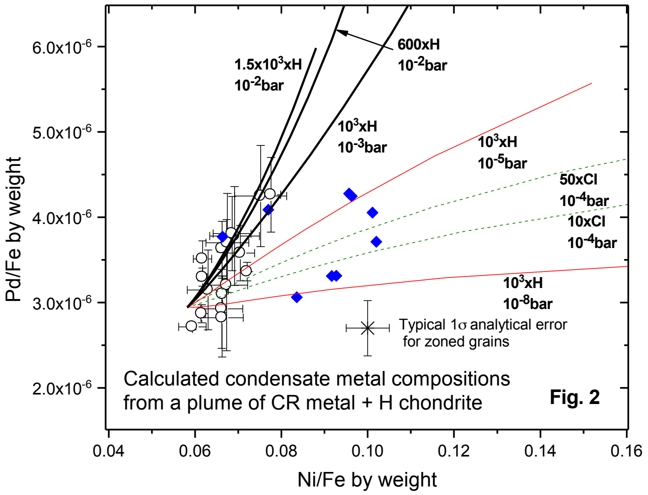

Fig. 2

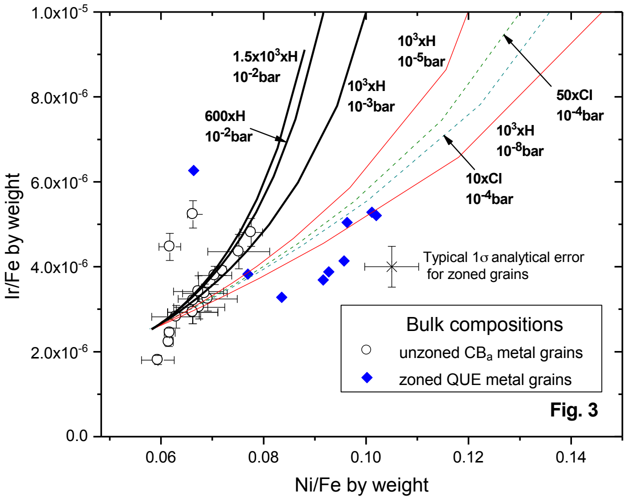

Fig. 3