ON MAKING CHONDRULES FROM MOLTEN PLANETESIMALS I. S. Sanders, Dept. of Geology, Trinity College, Dublin 2, Ireland (isanders@tcd.ie)

Introduction: This contribution is an update of the review by [1] of the splashing model for chondrule formation proposed by Zook [2]. The model contends that at least some, perhaps most, chondrules are frozen droplets of spray from impact plumes launched when thin-shelled planetesimals with fully molten interiors collided and merged at low speed. This idea is appealing because it seems to concur with much of what is known of the young protoplanetary disk. For example, it is probably no coincidence that during the first 2-3 Myr, while chondrules were being made, the disk was populated with molten planetesimals, probably melted by the decay of ^{26}Al, ready to burst open and spill their incandescent contents into space. The model provides ample energy for melting, and it circumvents the need for a special 'nebular' heat source because it does not invoke dust-clump precursors. It accounts for the retention of Na and FeO in crystallizing chondrule liquids because the droplets would have been very closely spaced in the early stages of plume expansion. Also other examples of frozen droplets in nature are interpreted as spray from large melt volumes, and never as melted dust clumps. However, the splashing model has its detractors and since 2012 the following arguments have been leveled against it.

Chronology: Pb-Pb dating by Connelly et al. [3] showed that some chondrules formed contemporaneously with CAIs. On the face of it this rules out splashing because planetesimals need time to melt. However, within the limits of quoted errors there would have been time for total internal melting to occur.

Melt composition: Johnson et al. [4] proposed that chondrules were formed by high-speed impact melting and jetting of primitive near-surface materials on colliding bodies. They claimed that low-speed disruption of molten bodies would have yielded fractionated chondrule compositions. The claim is unfounded because the splashing model invokes totally or near-totally molten planetesimal interiors which would have meant primitive magma chemistry.

Relict grains: Nagashima et al. [5] noted that the ubiquitous presence in Kakangari of relict ^{16}O-rich grains in chondrules suggests that they formed from precursor materials that had diverse O-isotope compositions. They felt this was inconsistent with formation of chondrules by splashing. However, the impact plume in the splashing model could plausibly have been contaminated with abundant ^{16}O-rich dust grains from the cool carapace of one or both colliding bodies. These dust grains could have become engulfed by the molten droplets they encountered, making them xenocrysts rather than 'relict grains'.

Complementarity: Palme et al. [6] noted that in CV chondrites the matrix typically has much higher Fe/Mg and Si/Mg than the bulk rock, which is solar, and chondrules have ratios lower than solar. They felt that this chemical 'complementarity' was inconsistent with the splashing model because it hints that chondrules and matrix were made together from a single reservoir prior to accretion. Complementarity is clearly an important constraint on chondrule formation, but an accepted mechanism for its origin is still awaited.

Complementarity in nucleosynthetic anomalies: Budde et al. [7] have extended the work of [6] by showing that bulk CVs have normal isotopic ratios for tungsten and molybdenum, yet chondrules and matrix carry complementary depletions and excesses, respectively, in s-process nuclides. This remarkable discovery is hard to reconcile with splashing because chondrules from a molten planetesimal would be expected to have the same uniform isotopic ratios as those in all differentiated meteorites. Also the chondrules are variably depleted in the s-process carrier, yet with splashing more uniform depletion might be expected.

Discussion: The splashing model can be reconciled with so many chondrule-forming constraints that the claim that it cannot explain complementarity needs careful scrutiny. A problem is that the dynamics of plume evolution and the state of the molten planetesimal interiors prior to splashing are poorly understood and difficult to simulate numerically [e.g. 8, 9]. Perhaps the 'dirty plume' scenario, which is invoked here for 'relict grains', may yet provide a way of creating complementary relations between chondrules and matrix. Perhaps a nucleosynthetic carrier phase in the dust was selectively incorporated into (or rejected by) the molten droplets. The possibilities offered by the splashing model, particularly in plume dynamics, need to be more fully explored before the significance of complementarity for the model can be understood.

References: [1] Sanders I. S. and Scott E. R. D. (2012) *Meteoritics & Planet. Sci., 47*, 2170-2192. [2] Zook H. A. (1980) *Meteoritics, 15*, 390–391. [3] Connelly J. N. et al. (2012) *Science, 338*, 651-655. [4] Johnson B. C. et al. (2015) *Nature, 517*, 339-341. [5] Nagashima K. et al. (2015) *GCA*, *151*, 49-67. [6] Palme H. et al. (2015) *EPSL, 411*, 11-19. [7] Budde G. et al. (2016) *EPSL, 455*, 293-303. [8] Dullemond C. P. (2014) *ApJ 794*, 91 (12pp). [9] Lichtenberg T. et al. (2016) *Icarus 274*, 350-365.