NEBULAR SHOCKS: CHONDRULE FORMATION OR DESTRUCTION? Emmanuel Jacquet[1,2] and Christopher Thompson[1], [1]Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St George Street, Toronto, ON, M5S 3H8, Canada, [2]Institut de Minéralogie, Physique des Matériaux et Cosmochimie, Muséum National d'Histoire Naturelle, 61 rue Buffon, 75005 Paris, France (emjacquet@mnhn.fr).

Introduction: Undoubtedly, chondrule formation ranks as one of the chief enigmas in cosmochemistry [1]. An enduring opinion since the 1980s has been that chondrules formed out of nebular precursors (that is, precursors grown in a disk environment, in contradistinction to planetary contexts; e.g. [2-3]) through some transient heating mechanism usually also envisioned in a nebular setting.

A leading idea in this vein is the shock scenario (e.g. [4-10]). Whether the shocks are supposed to arise from large-scale gravitational instabilities [8] or from planetary embryos in eccentric orbits [6,7], the basic tenet is that nebular solids ("protochondrules") are heated because of strong drag upon crossing the shock, before approaching thermal equilibrium with the hot, post-shock gas.

Despite the high level of theoretical development enjoyed by the shock scenario compared to other competing models and the successes encountered in matching the inferred thermal history of chondrules [11], a basic objection was first brought forward by [12-13]: protochondrules of different sizes would experience different drag decelerations, and would thus be led to collide at velocities well in excess of fragmentation thresholds (see Fig. 1).

Although [14] concluded that solar abundances (solid/gas mass ratio $\sim 10^{-2}$) would actually make such collisions infrequent, growing evidence from the FeO content of chondrule olivine [15], compound chondrule fraction [16] and retention of sodium [17] suggests that chondrule-forming regions were enriched in condensibles well above solar—in fact, this is the very reason for the increasing popularity of planetary scenarios (e.g. [18,19]). We have thus set out to reexamine the problem and in particular derive thresholds for the solid/gas mass ratio (henceforth called ε) leading to chondrule destruction [20].

Standard, gas-dominated shocks: We first considered standard gas-dominated ($\varepsilon \ll 1$) shocks. This situation lends itself to analytic treatment, supported by numerical calculations. Collision velocities were found to be generally within one order of magnitude of the velocity jump at the shock (which must be several km/s for chondrule melting temperatures to be obtained), so the destruction probability of a given protochondrule through catastrophic collision with another protochondrule could be safely equated to the probability of collision

$$P_{coll} = 1 - \exp(-\varepsilon/\varepsilon_{crit}) \quad (1),$$

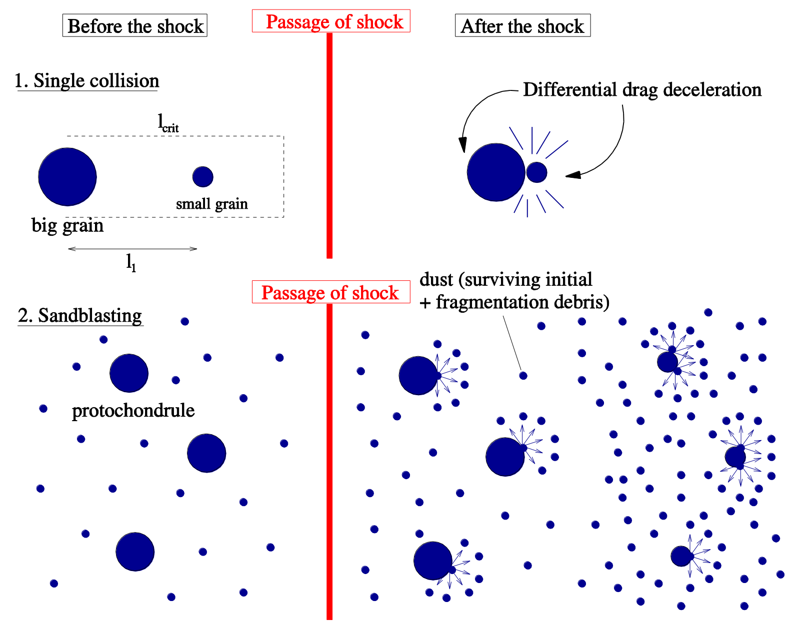

Figure 1: *Sketch of chondrule destruction process by collisions with peer chondrules (up) and with dust grains ("sandblasting"; bottom).*

where the critical solid/gas ratio ε_{crit} (corresponding to P_{coll} = 63 %) works out to ~0.1, assuming (conservatively) size distributions comparable to the ones presently observed in chondrites. This would barely allow one order of magnitude enrichment above solar values, which might be in tension even with type I chondrule data [21].

Yet this estimate ignores collisions between protochondrules and small (say micron-sized) grains. While individual such collisions would not lead to catastrophic disruption but merely eject *Y* times the impactor mass from the protochondrule (where *Y* is the velocity-dependent ejection yield), the effects of successive (numerous) collisions would add up. Moreover, the ejected dust would also contribute to further "sandblasting", hence a runaway erosion (see Fig. 1, 2). We found that the resulting critical solid/gas ratio would be of order Y^{-1} (with *Y* evaluated for the velocity jump). For *Y* of order 10^2-10^3 [22], this would allow essentially no enrichment above solar, although the rheology of liquids might complicate the picture.

Clearly, collisional destruction is a serious issue for standard shock models. We explored some variants which might alleviate the problem.

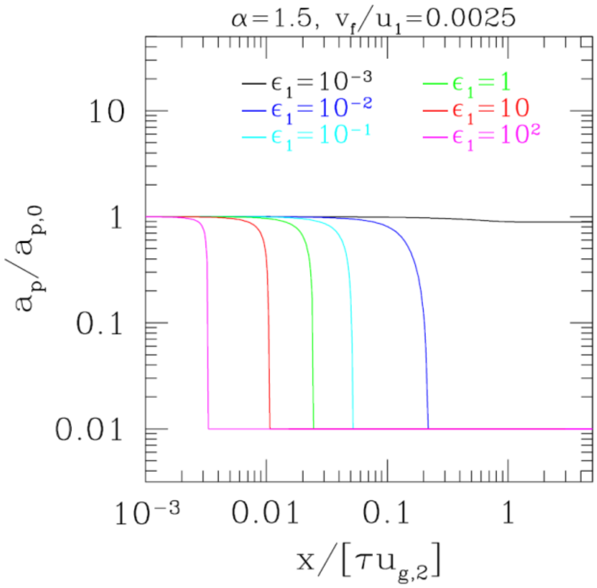

Figure 2: *Effect of sandblasting on the size of protochondrules (normalized to the initial one) as a function of distance to the shock front x (normalized to the stopping length).*

Small-scale bow shocks: Although the above reasoning is fairly independent of the overall structure and source of the shock, one basic assumption is that the shock is wider than the stopping length of the protochondrules. One could however envision a small-scale shock due to a few-km planetesimal [9]. The critical solid/gas ratio for protochondrule-protochondrule collisions would be somewhat increased and the threshold for sandblasting would be raised by 1 or 2 orders of magnitude. The heating event would last only a few seconds, not unlike the repeated flash heating envisioned by [23], and, at any rate, could account for some agglomeratic olivine objects [24] and igneous rims [25].

Solid-dominated shocks: Another regime hitherto little explored is that of a solid-dominated shock. Values of ε above 1 could result in the disk midplane from settling in a low-turbulence dead zone [26], possibly following some radial gas-solid redistribution (e.g. [27, 28]). In addition to satisfying empirical constraints on condensable element abundance, it would present the advantage of requiring fairly modest shock velocities (~2 km/s). While initial chondrule destruction would be extensive, given the high number density of the objects, there would be a prospect (absent from the gas-dominated case) of re-forming chondrules by coagulation once collision velocities allow sticking. In this case, though, the expected compositional homogeneization might be difficult to reconcile with the observed compositional diversity of chondrules ([3], [29]).

Reassessment of the evidence for condensable enhancement?: Finally, another way out—in the framework of the shock picture—may be to question the evidence for large solid abundances. In particular, one could relax the assumption that the ambient gas was of solar composition, as proposed by [6] who envisioned the contamination by an atmosphere outgassed by a planetary embryo. Such an explanation seems difficult to envision for large-scale shocks. With recent work casting doubt on the ability of the latter to account for the relatively rapid cooling rates of chondrules through sideway radiative losses [30], this may suggest that bow shocks are favored over large-scale shocks. At any rate, chondrule collisions remain a serious issue for the shock scenario as a whole.

References: [1] Boss A. P. (1996). Chondrules and the protoplanetary disk, Ed. Hewins, Jones, Scott, 257-263. [2] Taylor G. J. et al. (1983). Chondrules and their origins, LPI, 262-263. [3] Jacquet E. (2014), Icarus, 232, 176. [4] Desch S. J. & Connolly H. C. (2002), M&PS, 37, 183. [5] Morris M. A. & Desch S. J. (2010), ApJ, 722, 1474. [6] Morris M. A. et al. (2012), ApJ, 752, 27. [7] Boley A. C., Morris M. A., Desch S. J. (2013), ApJ, 776, 101. [8] Boss A. P. & Durisen R. H. (2005), ApJL, 621, L137. [9] Ciesla F. J. et al. (2004), M&PS, 39, 1809. [10] Susa H. & Nakamoto T. (2002), ApJL, 564, L57. [11] Desch S. J. et al. (2012), M&PS, 47, 1139. [12] Nakamoto T. & Miura H. (2004), LPSC XXXV, #1847. [13] Uesugi M. et al (2005). Chondrites and the Protoplanetary Disk, 893. [14] Ciesla F. J. (2006). M&PS, 41, 1347. [15] Grossman L. et al (2012), M&PS, 47, 2160. [16] Gooding J. L. & Keil K. (1981), Meteoritics, 16, 17. [17] Alexander C. M. O'D. et al (2008), Science, 320, 1617. [18] Symes S. J. K. et al (1998), M&PS, 33, 13-29. [19] Sanders I. & Scott E. R. D. (2012), M&PS, 47, 2170-2192. [20] Jacquet E. & Thompson C. (2014), ApJ, in press. [21] Tenner et al. (2014), GCA, in press. [22] Poelchau et al. (2012), M&PS, 48, 8. [23] Wasson J. T. (1996), Chondrules and the Protoplanetary Disk, 45-51. [24] Ruzicka A. et al (2012), M&PS, 76, 103. [25] Rubin A. E. (1984), GCA, 48, 1779-1789. [26] Gammie C. F. (1996), ApJ, 457, 355. [27] Youdin A. N. & Shu F. H. (2002), ApJ, 580, 494. [28] Russo M. & Thompson C. (submitted to ApJ). [29] Hezel D. C. & Palme H. (2007), GCA, 71, 4092. [30] Stammler S. M. & Dullemond C. P. (2014), Icarus, 242, 1-10.