THE FREQUENCY OF COMPOUND CHONDRULES AND IMPLICATIONS FOR CHONDRULE FORMATION. F. J.Ciesla,L.L.Hood, *DepartmentofPlanetarySciences/LunarandPlanetaryLaboratory,UniversityofArizona,TucsonAZ85721, USA (fciesla@lpl.arizona.edu).*

Introduction: Among the many properties of chondrules, compound chondrules, two chondrules fused together, have been studied to gain clues as to what the environment that chondrules formed in was like [1,2]. Two methods have been proposed for forming compound chondrules: collisions among individual chondrules while they were plastic [1] and melting of porous aggregates on an already existing primary chondrule [2]. If we can distinguish between these two scenarios, we will be able to gain further insight into how chondrules formed.

Previous Studies: Gooding and Keil [1] examined and classified chondrules in thin-section and by removal as whole pieces from meteorites. They concluded that approximately 4% of all chondrules are compounds, with compounds being more common among non-porphyritic chondrules (those that melted completely) than porphyritic. Based on their collisional modeling, these authors concluded that non-porphyritic chondrules were formed in regions of the nebula where the concentration of chondrule precursors was 10^2-10^4 times greater than it was where porphyritic chondrules formed.

Wasson *et al.* [2] examined approximately 10,000 chondrules in thin-section and identified 80 compound chondrules, of which they reported the sizes, contact angles, and textures of the compound components. In addition, these authors divided the types of compound chondrules into three groups: adhering, consorting, and enveloping. These authors acknowledged that they likely were missing some compound chondrules owing to their use of thin-sections, and thus multiplied their statistics by a factor of 3 to conclude that 2.4% of all chondrules are compounds. This factor was derived from the difference in population of compound chondrules observed in thin-section and by removal as whole pieces from meteorites by [1].

Thin-Section Biases: Because thin-section cuts will slice through compound chondrules with random orientations, it is possible that the thin-section will cut through the compound chondrule in such a manner that an observer would not be able to identify it as a compound. We have derived formulae for calculating the probability that a thin-section would cut an ahdering compound chondrule across the area of contact for the two components, allowing it to be identified. Averaged over all possible geometries, roughly 25% of all adhering and consorting chondrules and 50% of all enveloping chondrules would be identified in thin-section studies.

However, the probability that we derived for the adhering and consorting compounds depends on the contact angle between the two components. The smaller the contact angle, the less likely the thin-section cut would intersect it. Figure 1 shows the distribution of contact angles for these compounds as measured by [2]. We can correct each bin in the histogram by dividing the number of compounds in that bin by the probability that it would be detected by observation in thin-section. The results of this correction are shown in Figure 2.

Summing the number of compounds in each bin in Figure 2 gives 530 compound chondrules, which suggests that approximately 5% of all chondrules are adhering or consorting compounds. The number of enveloping chondrules does not significantly change this total. Figure 2 also strengthens the observation made by [2] that small contact angles are more common among adhering and consorting chondrules.

In addition, we calculate, based on the statistics of [2], that the compounds can be broken up into three categories based on the textures of their components: 71% are non-porphyritic-non-porphyritic, 4% are porphyritic-porphyritic, and 25% are mixed. Furthermore, of the secondaries (the most deformed component of the compounds), 92% are non-porphyritic and 8% are porphyritic. Thus, the obsevation that non-porphyritic chondrules are more frequently found as compounds is preserved in this study.

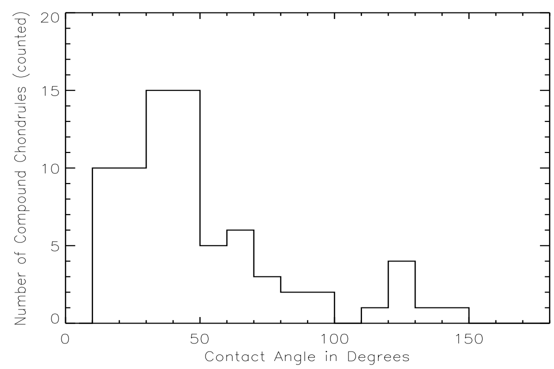

Figure 1: Histogram of contact angles for the 72 adhering and consorting compound chondrules a measured by [2]

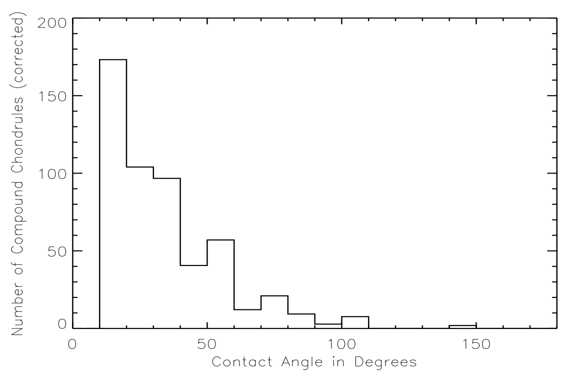

Figure 2: Corrected histogram of contact angles among adhering and consorting compound chondrules based on the data in Figure 1.

Discussion: Not only is it possible that a thin-section would slice through an adhering compound chondrule in a way that would not allow it to be identified as such, but it is also possible that the thin-section would slice through in a way to misidentify the compound chondrule. Figure 3 shows a three dimensional model of an adhering compound chondrule, where the lighter sphere represents the primary chondrule, and the darker represents the secondary. The primary in this model is a full sphere, whereas the secondary is a full sphere minus the part that would overlap the primary.

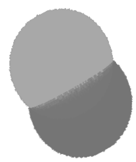

Figure 3: A model for an adhering compound chondrule. If a thin-section were cut near the line of centers, then the compound would be properly identified.

If a thin-section were cut near the line of centers of the compound chondrule in Figure 3, it is clear that this would allow the compound to be properly identified as adhering. However, Figure 4 shows a thin-section from this same compound cut perpendicular to the line of centers in the area where the two spheres intersect. In this thin-section, the compound would look like an enveloping compound. Thus, it is possible that at least some enveloping chondrules identified in thin-section are not a chondrule surrounded by another chondrule, but rather, an adhering compound that was sliced in a way to make it look like an enveloping one. While the probability for this is small, it may explain the fact that only a small fraction (7.5% in [2]) of compounds identified in thin-section are enveloping.

If compound chondrules formed by the melting of porous aggregates on a preexisting primary chondrule [2], then this study implies that more of those chondrules accreted fine dust between chondrule forming episodes than previously believed. If compound chondrules instead formed by collisions of plastic chondrules, then the regions of the nebula where chondrules formed had, on average, a higher number density of precursors than previously thought.

Figure 2 suggests that, if adhering compounds formed by the collisions of plastic chondrules, collisions were more frequent when the chondrules were not very deformable, thus the tendency for small contact angles. Chondrules were likely to be most deformable at higher temperatures. Thus, the distribution in Figure 2 can be explained by the collisional evolution of a swarm of particles as they cooled and became spatially concentrated (collision rate is proportional to number density of chondrules). Such a situation is predicted by the shock wave model for chondrule formation [3,4].

The fact that non-porphyritic chondrules are more common as secondaries than are porphyritic chondrules suggests that either non-porphyritic chondrules were formed in regions of the nebula with higher concentrations of chondrule precursors [1,3,4] or that non-porphyritic chondrules were more "efficient" at making compounds. The former possibility is consistent with the results of the shock wave models [3,4] which find that regions of the nebula with higher concentrations of chondrule precursors reach higher peak temperatures and cool more slowly than do regions with relatively low concentrations of chondrule precursors. However, if porphyritic chondrules are the result of incomplete melting of chondrule precursors, they are not likely to be be as deformable (rocks deform more easily at high temperatures, and surface tension decreases with increasing temperature), which may explain why of those compounds identified as having mixed textures, the textures of most secondaries (the more deformed as defined by [2]) is non-porphyritic. In previous studies of chondrule collisions, it has been assumed that all collisions among plastic chondrules results in fusing to form a compound. If this process was not 100% efficient, then it must be considered in the collisional evolution of chondrules.

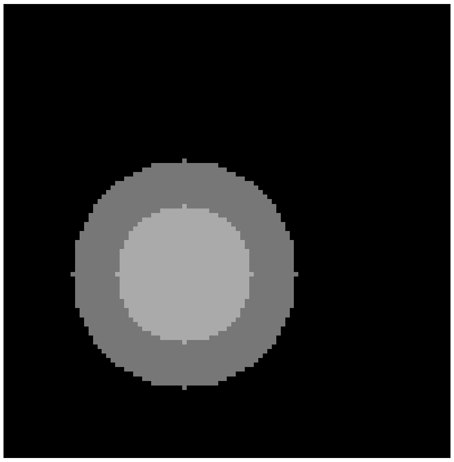

Figure 4: A possible thin-section slice of the compound chondrule shown in Figure 3. This slice was cut perpendicular to the line of centers of the compound chondrule such that it intersected the region where the spheres which make up the compound components overlapped. Rather than being identified as an adhering compound, this resembles an eveloping compound chondrule.

References: [1] Gooding, J. and K. Keil (1981) *Meteoritics* **16**, 17. [2] Wasson *et al.* (1995) *Geochim. Cosmochim. Acta* **59**, 1847. [3] Desch, S. and H. Connolly (2002) *Meteorit. Planet. Sci.* **37**, 183. [4] Ciesla, F. and L. Hood (2002) *Icarus* **158**, 281.