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The frequency of compound chondrules and implications for chondrule formation

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Abstract–The properties of compound chondrules and the implications that they have for the conditions and environment in which chondrules formed are investigated. Formulae to calculate the probability of detecting compound chondrules in thin sections are derived and applied to previous studies. This reinterpretation suggests that at least 5% of chondrules are compounds, a value that agrees well with studies in which whole chondrules were removed from meteorites. The observation that adhering compounds tend to have small contact arcs is strengthened by application of these formulae. While it has been observed that the secondaries of compound chondrules are usually smaller than their primaries, these same formulae suggest that this could be an observation bias. It is more likely than not that thin section analyses will identify compounds with secondaries that are smaller than their primaries. A new model for chondrule collisional evolution is also developed. From this model, it is inferred that chondrules would have formed, on average, in areas of the solar nebula that had solids concentrated at least 45 times over the canonical solar value.

INTRODUCTION

Studies of chondrules in thin sections and by removal as whole pieces from meteorites have shown that some chondrules are aggregates composed of two chondrules fused together. These compound chondrules have been interpreted by some as evidence that, during the time when they were molten, chondrules were susceptible to collisions (Gooding and Keil 1981). Some of these collisions would have resulted in chondrules sticking to one another or, in some cases, one chondrule completely enveloping another. Understanding these collisional histories, it was argued, would lead to a better understanding of the environment in which chondrules formed and provide greater insight into what was taking place in the solar nebula during the early part of solar system formation.

With this goal in mind, Gooding and Keil (1981) examined over 1600 chondrules in thin sections to find the distribution of chondrule textural types and the frequency of compounds. They also examined 216 whole chondrules removed from meteorites. Their study found that 4% of all chondrules exist as compound chondrules and that compound chondrules are more common among non-porphyritic chondrules than porphyritic chondrules. Therefore, Gooding and Keil (1981) argued that non-porphyritic chondrules formed in regions of the nebula that had a higher density of precursors than that of porphyritic chondrules.

An alternative formation mechanism for compound chondrules was proposed by Wasson et al. (1995). These authors suggested that some compound chondrules formed via collisions, while others formed when porous aggregates around a primary chondrule were flash heated and melted to form the secondary chondrule. Wasson et al. (1995) performed an even more comprehensive study by analyzing ~10,000 chondrules in 79 cm^2 of ordinary chondrite thin sections. These authors separated the compound chondrules into two categories: *siblings* with components that have similar textures and are thought to have formed via collisions in a single heating event and *independents* with components that have different textures and are thought to have formed in different heating events. In addition to characterizing all of the compounds they identified, these authors concluded that 2.4% of all chondrules are compounds. The reason for the different results of Gooding and Keil (1981) and Wasson et al. (1995) has been unclear, though the latter authors suggest it may be due to the fact that they did not include chondrules less than 40 μm in diameter in their statistics. Currently, this value of 2.4% is the accepted frequency of compound chondrules (Hewins 1997).

Distinguishing which of the two mechanisms was responsible for the formation of compound chondrules or understanding specifically when they operated would provide insights into how all chondrules formed. Thus, it is important to fully understand all of the properties of compound chondrules and to try to explain those properties in the context of a chondrule formation model.

The above studies have relied on thin section analyses of meteorites to identify the compound chondrules present in their samples. It has been shown that, because thin sections only sample a random slice of a chondrule, the uncertainties in where the cut intersects the chondrule can lead to biases in determining the chondrule size distribution (Eisenhour 1996). Gooding and Keil (1981) and Wasson et al. (1995) acknowledged that this uncertainty may have affected the statistics of compound chondrules in their studies. To correct for this source of error, they multiplied their thin section counts by a factor of 3, though the actual value of the correction factor is unknown (Wasson et al. 1995). This value was originally estimated by Gooding (1979) and was reinforced in Gooding and Keil (1981) by dividing the percent of compound chondrules found by removing whole chondrules from meteorites by the percent identified in a thin section. However, considering all uncertainties, the value could actually range from 2 to 4. Thus, a detailed understanding of the biases associated with identifying a compound chondrule in a thin section is needed to interpret thin section statistics.

In this study, some of the issues surrounding compound chondrule formation are re-examined. In the next section, some of the problems of identifying compound chondrules in thin sections are quantitatively discussed, and the theoretical correction factors needed for estimating the population of compound chondrules from such studies are derived. These factors are applied to the compound chondrule statistics of Wasson et al. (1995) in the Application to Compound Statistics section to re-evaluate the frequency of compound chondrules. In the General Model for Chondrule Collisional Evolution section, a new model for chondrule collisional evolution is developed and applied to conditions plausible for chondrule formation. In the Requirements for Sticking in Chondrule Collisions section, some implications for this study are discussed in the context of chondrule formation.

THIN SECTION STUDIES

In addition to dividing compound chondrules into siblings and independents, Wasson et al. (1995) categorized them on the basis of their geometries as: adhering, consorting, and enveloping. Adhering and consorting compounds are those in which the contact arc (angular distance along the primary chondrule in contact with the secondary, where the secondary is the more deformed component) between the components never reaches more than 180°. Enveloping chondrules are those which appear to have contact arcs greater than 180°. Consorting compounds and adhering compounds are similar and are distinguished by the apparent ratio of diameters of the primary and secondary chondrules in a thin section. For the purposes of this work, no distinction is made between adhering and consorting chondrules as the used methods can be applied to both.

When considering thin section studies of chondrules, it is important to realize that the thin sections are approximately 30 μm thick. For a compound to be identified, the thin section must cut through the compound such that both components are included within the thickness of the thin section. If not, light may not be transmitted through one of the components, making it appear that the compound is a single chondrule and, thus, leading to underestimates in the number of compounds present in the sample. In addition, as discussed by Eisenhour (1996), thin section studies likely do not report the correct sizes of the chondrules that are studied. In this section, equations are derived to correct compound chondrule statistics for the uncertainty of where the thin section slices through the compound. The considered thin section is assumed to have negligible thickness. In the future, consideration should be made for how a finite thickness for the thin section affects the results.

Adhering Compounds

First, consider two spheres joined together such that they would be defined as an adhering compound (Fig. 1). The primary is defined as a sphere with radius, a, and the secondary is characterized by a mean radius, b (mean radius is used here because the secondary shape may not be spherical). For simplicity, the chondrules are assumed to be symmetric about the line that connects their centers. Following Wasson et al. (1995), the contact arc, φ, is defined as the angular distance along the primary that is in contact with the secondary. The corresponding angle, γ, is defined as the angular distance along the secondary that is deformed by the primary. For this case, φ is defined as the maximum contact arc, that is, the contact arc perpendicular to the line of centers. The chord that connects the two ends of the contact (the length of the contact) is defined as s and is equal to:

$$s = 2a\sin\left(\frac{\varphi}{2}\right) \quad (1)$$

If a thin section slices through this compound chondrule, an angle, β, will be formed between the plane of the thin section and the line of centers of the chondrule.

Projected onto a line perpendicular to the thin section, the height of the compound is:

$$h_{proj} = \max\left[2a,\ 2b,\ a + b + \left(a\cos\frac{\varphi}{2} + b\cos\frac{\gamma}{2}\right)\sin\beta\right] \quad (2)$$

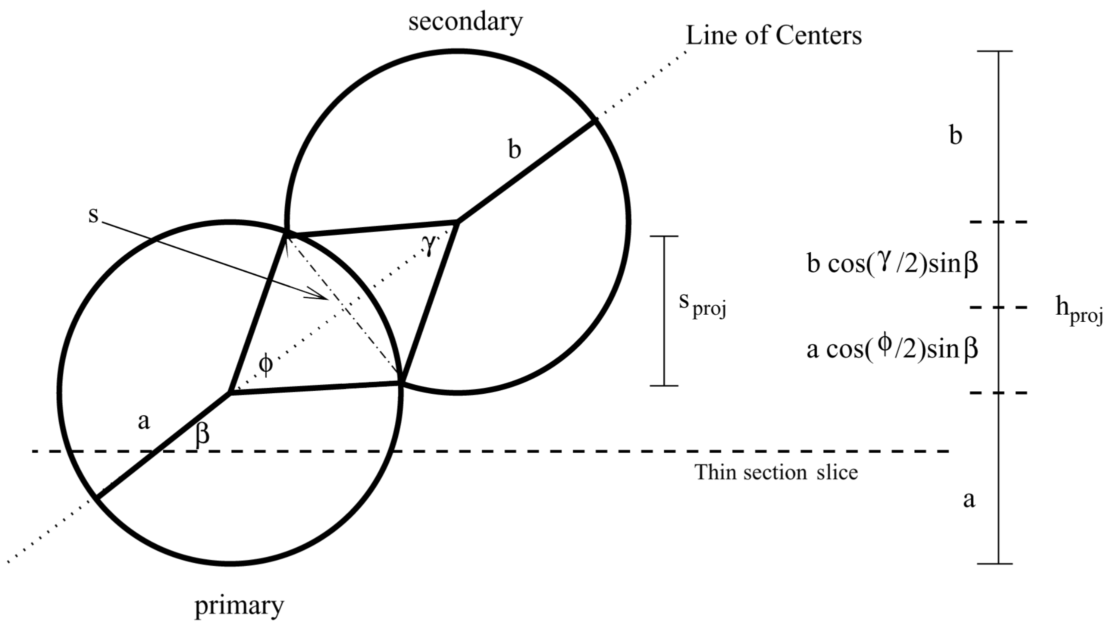

Fig. 1. The geometry and defined terms for the calculations involving adhering compound chondrules. The compound is assumed to be made up of two spheres, with the primary chondrule having radius a and the secondary having radius b. The contact between the two components is an arc, φ, measured along the primary such that it passes through the line of centers. The actual length of this contact is s = 2a sin(φ/2). This same contact subtends an arc, γ, along the secondary. The two angles can be related through the equation: a sin(φ/2) = b sin(γ/2). The probability of a thin section slicing through the compound such that it would be identified as such is the length of the contact projected onto a plane perpendicular to the thin section cut, s_{proj}, divided by the projected height of the compound, h_{proj}.

The projection of the contact chord onto a line perpendicular to the thin section is s cosβ. If a thin section slices through this area of contact, it will be identified as an adhering compound chondrule; if it does not contain the contact area, it will not be identified as such. Therefore, assuming the thickness of the thin section is small compared to the total height of the chondrule, the probability that the area of contact is also contained in that thin section is the height of the contact divided by the height of the compound (s_{proj}/h_{proj}):

$$P(\varphi, \beta, a, b) = \frac{2a\sin\frac{\varphi}{2}\cos\beta}{\max\left[2a,\ 2b,\ a+b+\left(a\cos\frac{\varphi}{2}+b\cos\frac{\gamma}{2}\right)\sin\beta\right]} \tag{3}$$

We can reduce the complexity of this relation by introducing the variable:

$$r = \frac{b}{a} \tag{4}$$

Also, we can eliminate γ from the equations by using:

$$a\sin\frac{\varphi}{2} = b\sin\frac{\gamma}{2} \tag{5}$$

This allows us to make the substitution:

$$b\cos\frac{\gamma}{2} = \sqrt{b^2 - a^2\sin^2\frac{\varphi}{2}} \tag{6}$$

Making this substitution and making use of the variable, r, we can rewrite Equation 3 as:

$$P(\varphi, \beta, r) = \frac{2\sin\frac{\varphi}{2}\cos\beta}{\max\left[2,\ 2r,\ 1+r+\left(\cos\frac{\varphi}{2}+\sqrt{r^2-\cos^2\frac{\varphi}{2}}\right)\sin\beta\right]} \tag{7}$$

To calculate the probability that a given compound chondrule will be identified in a thin section cut with an arbitrary orientation, it is necessary to average over all β and r. Averaging over all β would give:

$$P(\varphi, r) = \frac{\int_0^{\pi/2} P(\varphi, \beta, r)\,d\beta}{\int_0^{\pi/2} d\beta} \tag{8}$$

assuming that any value of β between 0 and π/2 is equally possible. Because the denominator of P(φ, β, r) will have different values under different conditions, it is necessary to break up the integral for different cases. For r <1:

$$P(\varphi, r<1) = \frac{2}{\pi}\left[\int_0^{\beta_c} \sin\left(\frac{\varphi}{2}\right)\cos\beta d\beta \right. \tag{9}$$

$$\left. + \int_{\beta_c}^{\pi/2} \frac{2\sin\left(\frac{\varphi}{2}\right)\cos\beta d\beta}{1+r+\left(\cos\frac{\varphi}{2}+\sqrt{r^2-\cos^2\left[\frac{\varphi}{2}\right]}\right)\sin\beta}\right]$$

where β_c is defined as:

$$\beta_c = \sin^{-1}\left[\frac{1-r}{\cos\left(\frac{\varphi}{2}\right)+\sqrt{r^2-\cos^2\left(\frac{\varphi}{2}\right)}}\right] \tag{10}$$

The value of β_c represents the transition point for β where the maximum height of the compound is not just the height of one of the components but, rather, is determined by some combination of the radii of the two components. We can evaluate the integral given in Equation 9 and substitute in this expression for β_c to get:

$$P(\varphi, r<1) = \frac{2\sin\left(\frac{\varphi}{2}\right)}{\pi\left[\cos\left(\frac{\varphi}{2}\right)+\sqrt{r^2-\sin^2\left(\frac{\varphi}{2}\right)}\right]} \tag{11}$$

$$\left[1-r+2\ln\left(\frac{1+r+\left[\cos\left(\frac{\varphi}{2}\right)+\sqrt{r^2-\sin^2\left(\frac{\varphi}{2}\right)}\right]}{2}\right)\right]$$

These expressions are only valid when

$$\varphi < 2\sin^{-1}(r) \tag{12}$$

otherwise, it becomes necessary to take the square root of a negative value. This issue is discussed further below but is only important when contact arcs are large, which is rare.

Similarly, we can define the probability for $r>1$:

$$P(\varphi, r>1) = \frac{2}{\pi}\left[\int_0^{\beta_c} \frac{1}{r}\sin\left(\frac{\varphi}{2}\right)\cos\beta d\beta \right. \tag{13}$$

$$\left. + \int_{\beta_c}^{\pi/2} \frac{2\sin\left(\frac{\varphi}{2}\right)\cos d\beta}{1+r+\left(\cos\frac{\varphi}{2}+\sqrt{r^2-\cos^2\left[\frac{\varphi}{2}\right]}\right)\sin\beta}\right]$$

where β_c here is defined as:

$$\beta_c = \sin^{-1}\left[\frac{r-1}{\cos\left(\frac{\varphi}{2}\right)+\sqrt{r^2-\cos^2\left(\frac{\varphi}{2}\right)}}\right] \tag{14}$$

Thus:

$$P(\varphi, r>1) = \frac{2\sin\left(\frac{\varphi}{2}\right)}{\pi\left[\cos\left(\frac{\varphi}{2}\right)+\sqrt{r^2-\sin^2\left(\frac{\varphi}{2}\right)}\right]} \tag{15}$$

$$\left\{\frac{r-1}{r}+2\ln\left[\frac{1+r+\cos\left(\frac{\varphi}{2}\right)+\sqrt{r^2-\sin^2\left(\frac{\varphi}{2}\right)}}{2}\right]\right\}$$

This expression is valid for all values of φ.

Averaging over all r is not as simple as it is for β. It is doubtful that all values of r are equally probable because chondrules tend to have a restricted range of sizes (0.1–1 mm). In fact, each type of chondritic meteorite has a different average chondrule diameter (Jones et al. 2000), a value that would be meaningless if any size was equally possible.

To average over all values of r, the distribution of chondrule sizes must be known. Wasson et al. (1995) found an average value of r of approximately 0.25 in their samples, though the real value may differ due to the same uncertainty of where the thin section intersects the compound. However, Cuzzi et al. (2001) have argued that chondrules could have been concentrated in regions of the nebula by turbulence and that this mechanism preferentially concentrates particles of the same size. This issue will be discussed further below.

Figure 2 shows the probability of identifying a compound as a function of contact angle for three different values of r. The line for r = 0.25 ends at roughly 30° for the reason described above. This plot, along with Equation 7, shows that the probability of identifying a compound chondrule is lower for larger values of r. This can also be seen in the different relations for P (φ; r) derived above. The reason for the result has to do with the fact that the length of the contact s, is 2a sin(φ/2). In terms of r, the contact has a length of 2(b/r) sin(φ/2). Thus, for two compounds with secondaries both with effective radii of b, the one with the larger contact (and higher probability of being detected) will be the one with the smaller r (larger a).

Another way of thinking about it is when r is small, the height of the compound is not significantly greater than 2a, and thus, the ratio of contact height to compound height is ~sin(φ/2). However, when r is large, s has the same relation, but the height of the compound is not significantly greater

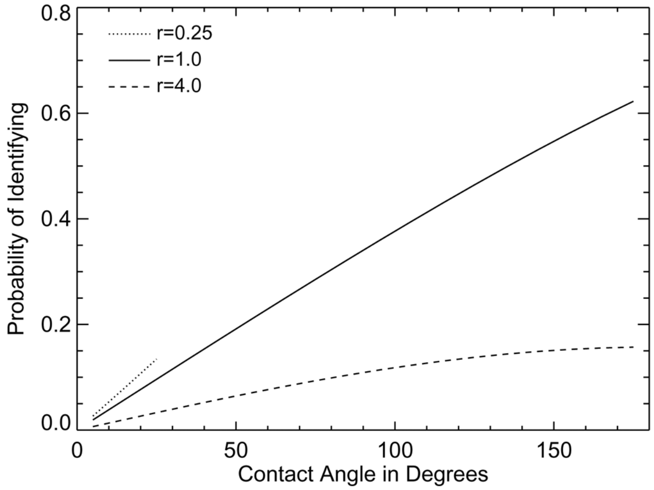

Fig. 2. The theoretical probability of identifying an adhering compound chondrule in a thin section as a function of the contact arc along the primary chondrule. Three cases for various ratios of sizes between the primary and secondary are plotted. The geometry of compounds used here does not allow for contact arcs greater than 30 degrees for the case of r = 0.25.

than 2b, and thus, the ratio goes as ~sin(φ/2)/r. Therefore, it is more probable to observe compounds with secondaries that are small compared to the primaries. This is what was observed by Wasson et al. (1995). It cannot be known for certain whether the observation that secondaries are smaller than primaries is due to the biases such as those described or is a real feature of compounds. Clearly, more work is needed to investigate this. For the rest of this study, we will assume that r = 1 for the detailed quantitative adjustments to the thin section studies, but we will discuss the effects that different values of r would have.

Thus, assuming explicitly r = 1:

$$P(\varphi) = \frac{2}{\pi}\ln\left[1 + \cos\left(\frac{\varphi}{2}\right)\right]\tan\left(\frac{\varphi}{2}\right) \quad (16)$$

Considering those contact arcs that measure between 0 (which would be two spheres tangent to one another) and π/2 (the same angular range that Wasson et al. [1995] defined for adhering chondrules), the probability that the two chondrules would be identified as compounds in the thin section slice is:

$$P = \frac{\int_0^{\pi} P(\varphi)d\varphi}{\int_0^{\pi} d\varphi} \quad (17)$$

which is roughly 25%. In other words, when a thin section slice intersects a compound chondrule with r = 1, there is a 75% chance that it will not be identified as such, which means that thin section statistics would have to be multiplied by 4 to extend to the population of whole chondrules. This assumes that there is no preferred contact arc, i.e., that it is equally probable for any contact arc to exist (this issue is discussed in the Application to Compound Statistics section).

Enveloping Compounds

Compound chondrules may also occur as enveloping chondrules, where one chondrule is surrounded by another (Fig. 3). Assuming that the inner chondrule has a radius b and the outer chondrule extends some radius, a, from the center of the compound chondrule, then the probability that a thin section cut will intersect both chondrules is the diameter of the inner chondrule divided by the diameter of the outer chondrule which reduces to the ratio of their effective diameters:

$$P(a, b) = \frac{2b}{2a} \quad (18)$$

Averaging over all possible ratios, the total probability of being able to identify an enveloping chondrule is:

$$P = \frac{\int_0^{1} r dr}{\int_0^{1} dr} \quad (19)$$

or 50%, implying that the correction factor for these types of compounds is 2. This is an approximate value, however, because if the inner chondrule is only slightly cut by the thin section (that is, b << a), it may mistakenly be identified as a relict grain.

APPLICATION TO COMPOUND STATISTICS

Wasson et al. (1995) identified and described 80 compound chondrules that comprised about 0.8% of all chondrules observed in a thin section. Of those, 74 were classified either as consorting or adhering chondrules. As mentioned above, these authors multiplied by a factor of three to account for biases due to observing objects in a thin section. This factor was applied for all compound chondrules regardless of contact geometry. However, Equation 16 suggests that the probability of identifying a compound chondrule in a thin section is dependent on the contact arc between the primary and secondary. This warrants further investigation.

Figure 4 shows the distribution of contact arcs for adhering chondrules measured by Wasson et al. (1995). It was found that if there were no preferred distribution of contact arcs, the correction factor for extrapolating thin section counts to the total chondrule population would be a factor of 4 (close to the value of 3 used by previous studies). However, Fig. 4

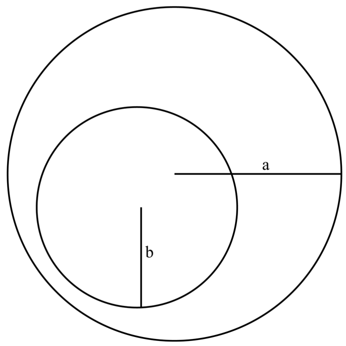

Fig. 3. The geometry and defined terms for the calculations involving enveloping compound chondrules. The primary chondrule is assumed to be a sphere of radius, b, and the secondary forms a sphere of radius, a. The probability of a thin section slicing through the compound such that it would be identified as such is the diameter of the primary divided by the diameter of the secondary.

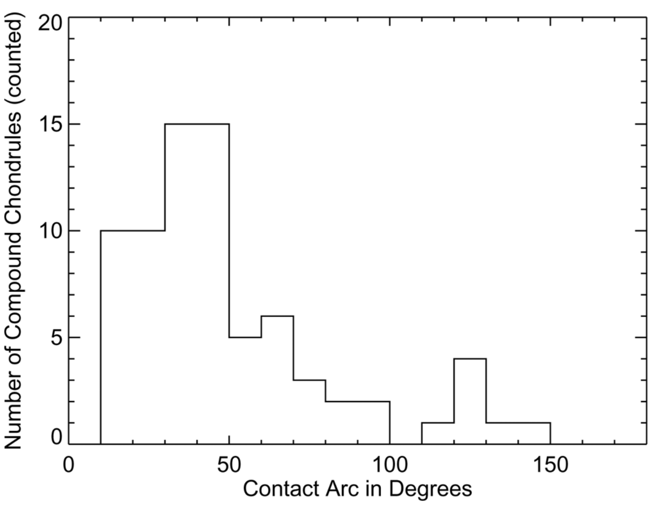

Fig. 4. A histogram that shows the distribution of contact arcs for the adhering and consorting compound chondrules observed in thin section by Wasson et al. (1995) is plotted. The angles are distributed in 10° bins.

suggests that there is a preference for low (<90°) contact arcs among adhering chondrules. According to Equation 16, these low angles have a relatively low probability of being observed in a thin section. Therefore, the geometries of compound chondrules must be considered in correcting for underestimates. In this work, no distinction is made between sibling and independent compounds as defined by Wasson et al. (1995). They are treated together. Wasson et al. (1995) argued that the different textures and compositions of the components in independent compounds suggest that they were formed in different heating events. This need not be the case, as is discussed further below.

The contact arc observed for adhering chondrules in a thin section is likely not equal to the maximum contact arc. For this to be the case, the thin section would have to intersect the compound chondrule exactly at the center of the contact between the two components. In reality, the thin section cut is likely to intersect the contact area at any point with equal probability. If we assume that the contact area is a circle with radius s/2, then the thin section will, on average, cut the contact at a distance s/4 from the center of the arc, as illustrated in Fig. 5. The chord labeled "Average Intersection" should be taken as the average location in the contact of an adhering chondrule where the thin section passes through. The length of this chord, s relative to the diameter of the contact, s_{max}, is:

$$s = \frac{\sqrt{3}}{2} s_{max} \tag{20}$$

Thus, the contact arc at this point can be related to the maximum contact arc by the following formula:

$$\sin\left(\frac{\varphi_{mean}}{2}\right) = \frac{\sqrt{3}}{2}\sin\left(\frac{\varphi_{max}}{2}\right) \tag{21}$$

where φ_{mean} is the average contact arc of a thin section cut, and φ_{max} is the maximum contact arc that could be cut from a compound chondrule if it were cut along its line of centers. Thus, Fig. 4 may only represent a histogram of the average contact arc, φ_{mean}, rather than the maximum contact arc for which Equation 16 was derived. Applying the above relation to each of the contact arcs in Fig. 4 gives the modified distribution in Fig. 6. While the distribution has moved to the right (toward higher contact angles), the tendency for small contact arcs is still noticeable. The adjustment described here causes some of those compounds with large contact arcs (>90°) to be pushed beyond 180°, pushing them from the adhering label to the enveloping label.

Figure 7 shows the adjusted distribution of contact arcs based upon the measurements of Wasson et al. (1995). This distribution was obtained by taking the histogram of Fig. 6 and applying a correction factor (found by calculating the probability of detecting a compound chondrule using Equation 16 and then taking the inverse) to each individual bin for the case when the radius of the primary is equal to the radius of the secondary (a = b). The bins are 10° wide, and the correction factor was evaluated for the middle angle of each bin. This procedure was repeated with bins 1, 5, and 20 degrees wide, and the results did not change significantly.

Figure 7 shows that the distribution of the contact arcs is dramatically changed by considering the angular dependence of the correction factors. Summing up the corrected values from each bin yields a total number of compound chondrules of ~520, implying that ~5.2% of all chondrules are adhering compounds. The shape of the distribution shown in Fig. 7 will be discussed below. To be complete, we also considered cases where r = 0.25 (the average value found by Wasson et al. [1995]) and r = 4. Under these assumptions, the population of compounds is 3.7% and 15%, respectively. In both cases, the general shape of the histograms would be similar to that shown in Fig. 7, with small contact arcs being more common

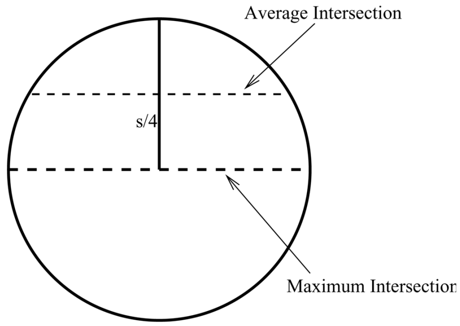

Fig. 5. Taking this circle with a diameter of s to represent the shape of the contact between two adhering chondrules, a thin section will slice through the contact, on average, at a distance of s/4 from the center. The maximum intersection, for which the equations in this study are derived, would require the thin section to slice through the center.

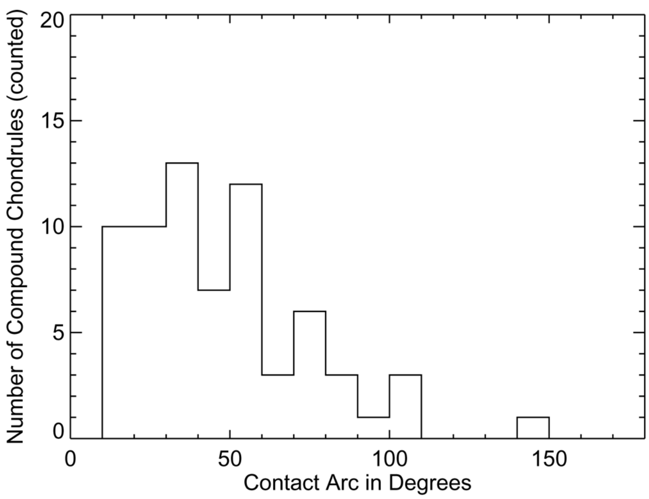

Fig. 6. Same distribution of contact arcs as in Fig. 4 but modified to account for the likelihood of a thin section slice cutting through a random section of the contact of a compound chondrule as illustrated in Fig. 5. This correction pushes the distribution to higher contact angles but shows that most compound chondrules have small contact angles.

than large ones. Because only a small number of enveloping chondrules have been observed, they are a minor component of the population. To be conservative, due to the simple geometries used in deriving the equations in the Thin Section Studies section and the uncertainty in what values of r to use, we estimate that ~5% of all chondrules are compounds.

The value of 5% attained here compares favorably with the findings of Gooding and Keil (1981). These authors found that 9 of 216 (~4.2%) whole chondrules removed from meteorites were compounds. The results of this study are within one standard deviation, 1.4%, of this value. This point is worth noting because the biases that are corrected for in this study would not exist in a study of whole chondrules. Gooding and Keil (1981) also studied chondrules in thin sections and identified 1.4% of their sample (~1600 chondrules) as being

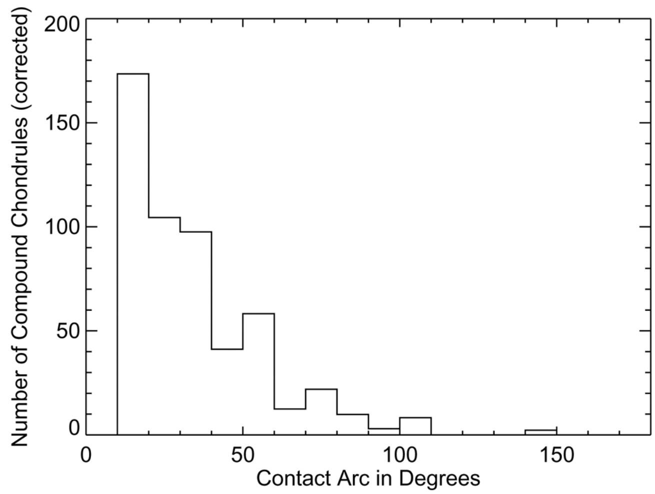

Fig. 7. The same data as in Fig. 4 after the correction factor (found using Equation 13) was applied to each bin is shown. Because compounds with small contact arcs are much less likely to be observed by thin section analysis, correcting for this implies that there are a large number of them. This supports the idea that compound chondrules tend to have small contact arcs.

compounds. Because no geometries were reported along with these statistics, their results cannot be compared with the findings of this work. Also, note that this assumes that there were no biases associated with the whole chondrule studies. Possibly, a small adhering secondary on a chondrule could be missed in the rough surface of the chondrule. This particular case would imply that Gooding and Keil (1981) put a lower limit on the frequency of compounds.

Because Wasson et al. (1995) also documented the textures of the components in the compounds they observed, the compound chondrules can be grouped into the following categories: porphyritic-porphyritic (PP), non-porphyritic-non-porphyritic (NN), and mixed (M) (there were three compounds not included in this analysis because the textures of individual compound components were not unique). By making histograms for each of these categories and correcting for biases as described above, we found that of all compound chondrules, 71% are NN, 25% are M, and 4% are PP (though the identification of PP compounds is difficult, as noted by Wasson et al. (1995), due to the fact that the boundaries between the components are less clear than in the other types). In addition, 92% of all secondaries are non-porphyritic, while 8% are porphyritic. These numbers do not change significantly for various values of r. These statistics will be discussed further below.

A GENERAL MODEL FOR CHONDRULE COLLISIONAL EVOLUTION

Having identified the fraction of chondrules that are compounds, a collisional model is needed to provide insight into the environment in which they may have formed. Even if some compound chondrules formed by the alternative method proposed by Wasson et al. (1995), collisions among chondrules may have occurred. In fact, these authors argued that such collisions are likely responsible for sibling chondrules (those they believed formed in the same heating event), which make up ~60% of all compounds. Therefore, a comprehensive model for chondrule collisional evolution is needed to understand how compound chondrules could form in this manner.

Gooding and Keil (1981) used principles from the kinetic theory of gases to calculate a collision rate for chondrules. They found the collisional probability to be:

$$P = \sqrt{2}\pi v d^2 n_c t_{plas} \tag{22}$$

where v is the average relative speed of the chondrules, d is the chondrule diameter, n_c is the number density of the chondrules, and t_{plas} is the period of time during which chondrules are plastic, taken here and in other work (Desch and Connolly 2002) to be the time during which the chondrules are at temperatures above their solidus. Note that this equation does not allow predictions to be made about the number of collisions that would produce multiple compound chondrules (three or more chondrules fused together). Such an outcome is possible, especially if t_{plas} approximates thousands of seconds, as suggested by recent studies (Desch and Connolly 2002; Ciesla and Hood 2002). To fully investigate the collisional history of chondrules, the principles of kinetic theory for a multi-species gas can be applied to extend the model of Gooding and Keil (1981).

The number of collisions per unit volume per unit time between two species, A and B, is (Vincenti and Kruger 1965):

$$Z = \frac{n_A n_B}{\sigma}\pi d_{AB}^2 v_{AB} \tag{23}$$

where n_A and n_B are the number densities of species A and B, $d_{AB} = (d_A + d_B)/2$, where d_A and d_B are the diameters of the respective species, v_{AB} is the average relative velocity of A with respect to B, and σ is a correction factor. If A = B, then $\sigma = 2$; otherwise, $\sigma = 1$. (Note that to avoid double counting of collisions, this factor was not included in the analysis of Gooding and Keil [1981].) For gas molecules:

$$v_{AB} = \left(\frac{8kT}{\pi m_{AB}}\right)^{\frac{1}{2}} \tag{24}$$

where k is Boltzmann's constant, T is the temperature of the gas, and m_{AB} is defined as:

$$m_{AB} = \frac{m_A m_B}{m_A + m_B} \tag{25}$$

where m_A and m_B are the masses of a molecule of A and B, respectively. For the purposes of this study, v_0 is defined as the average velocity of a single chondrule, and the average velocities of agglomerates scale with mass in the same manner as the gas molecules above. Therefore, when two agglomerates composed of i and j chondrules, respectively, are considered, the relative velocity of the two will be:

$$v_{ij} = \sqrt{\frac{i+j}{ij}}v_0 \tag{26}$$

This equation for the velocity is derived under the assumption that the collisions between chondrules are elastic. Collisions between chondrules likely led to a loss of some kinetic energy as the particles deformed. This loss of energy would result in lower final velocities than calculated here. Because the collisional rate is proportional to the relative velocity, it is implied that the model here overestimates the number of collisions that would take place. Thus, this model should be considered an extension of the model of Gooding and Keil (1981) but not a complete treatment. A complete treatment would consider the inelastic collapse of a swarm of particles (Schorghofer and Zhou 1996).

In this model, the effective diameters of the agglomerates scale as the geometric mean of their most extreme axes, i.e., the axes that the agglomerates would have if all the constituent chondrules were collinear. Thus, for an agglomerate made up of i chondrules, its effective diameter would be:

$$d_i = i^{\frac{1}{3}} d_1 \tag{27}$$

where d_1 is the diameter of a single chondrule.

This model allows an initial number density of single chondrules to be set and then calculates the number of collisions that will occur for every time step through the period under consideration. Thus, in a given time step, we calculate the number of collisions between agglomerates with i chondrules and j chondrules where i and j are integers and i <j. For every collision that occurs, the number of agglomerates with i + j chondrules increases by one, and the number of agglomerates with i and j chondrules both decrease by 1. At the end of each time step, the new size distribution is calculated, and the process is repeated. Mathematically, we are solving a situation similar to that described by the Smoluchowski equation (e.g., Kolesnichenko 2001), written in our notation as:

$$\frac{\partial n_L}{\partial t} = \sum_{i=0}^{N}\sum_{j=1}^{N+1} - \sum_{i=0}^{N+1} Z_{Li}\sigma \tag{28}$$

where L = i + j, the Z terms are derived from the collision frequencies as described above, σ is the correction factory described above, and N represents the upper limit of the size of agglomerates being considered (chosen here to be 30, since no clusters grow nearly that large in our studies). The time step is chosen such that changes to the size distribution are small over that interval.

Figure 8 shows the results of some model runs for different concentrations of particles. A solar composition (concentration factor = 1) is defined as that where all solids are in the form of chondrules with a mass ratio of solids to gas of 0.005. The gas density was assumed to be 10^{-8} g cm^{-3}, which is reasonable for a post-shock region of the solar nebula where chondrules may have formed. (Note: we use values typical for regions of the nebula that were overrun with shock waves because cooling rates and densities of solids have been covered in detail in recent studies. Below, we discuss how results would change if chondrules formed by some other mechanism.) A chondrule mass density of 3.0 g cm^{-3} is assumed, and all chondrules are treated as 0.6 mm-diameter spheres (a value used so that the results can be compared to work of other authors). This gives a solar number density for the chondrules, n_c, of 1.5×10^{-7} cm^{-3}. The relative velocity of the chondrules with respect to one another, v, is assumed to be 100 cm s^{-1}. This velocity is roughly that expected for chondrule-sized objects in a solar nebula with a turbulence parameter, α, of order 10^{-4} (Cuzzi et al. 1998; Desch and Connolly 2002). Higher velocities likely would have resulted in disruption of the chondrules rather than fusing. In fact, Kring (1991) argued, based on surface tension calculations, that chondrules would be disrupted rather than fused if collisions took place at velocities greater than 130 cm s^{-1}.

In these calculations, it is assumed that all collisions lead to compound chondrule formation (sticking). Likely, some collisions occurred that led to the disruption of the chondrules during their formation. Thus, collisions were possibly more common than is indicated by the compound chondrule record, and thus, the collisional frequencies and inferred chondrule concentrations presented here are lower estimates.

Figure 8 plots the fraction of double chondrules (two chondrules fused together) that result in clusters of given concentrations after 10^4 sec have elapsed (the assumed plasticity time). The plasticity time here is assumed to be equal to the amount of time that the chondrules remained above temperatures of 1400 K in the model runs presented in Desch and Connolly (2002). This temperature was chosen to represent the lowest temperature at which silicate melt would be present in the chondrule (approximate solidus) and will be discussed further below. In their original work, Gooding and Keil (1981) assumed that the lower bound on the "plasticity" temperature was the glass transition temperature (~900 K). Here, we take a more conservative value. We should point out that the time that it takes for chondrules to cool below 1400 K decreases with an increased concentration of particles in the models of Desch and Connolly (2002) and Ciesla and Hood (2002). The 10^4 seconds found by Desch and Connolly (2002) is assumed to be a maximum time during which chondrules are plastic. Other models and other chondrule formation mechanisms tend to predict shorter cooling times. The implications of using a shorter t_{plas} are discussed below.

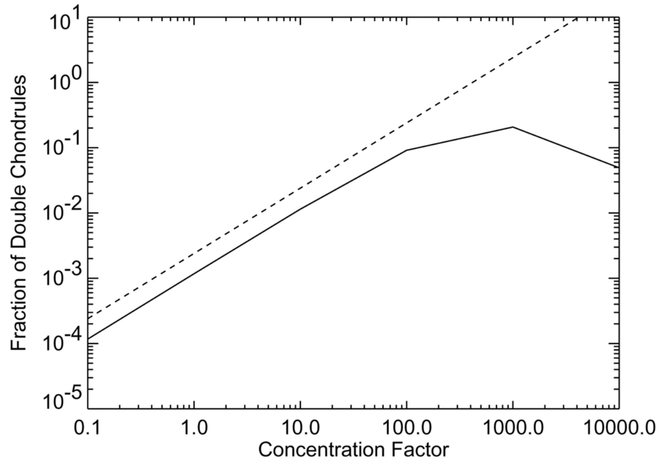

Fig. 8. The fraction of double chondrules predicted for different concentrations of chondrules. The chondrules were assumed to have diameters of 0.6 mm, were plastic for 10,000 seconds, and had mean relative velocities of 100 cm/s. Our model (solid line) predicts fewer doubles than does that of Gooding and Keil (dashed line).

The solid line in Fig. 8 represents the results of the model presented here, while the dashed line represents the predictions made by the equation given in Gooding and Keil (1981). The difference in the two models at low concentrations is a factor of 2, which comes from the correction factor that Vincenti and Kruger (1965) introduce (the σ term in the collision frequency equation above). As concentrations get higher, the difference grows. This is because, at higher densities, the double chondrules are susceptible to collisions as well and, therefore, are being destroyed as well as created. Also, the Gooding and Keil model was meant to predict a small number of collisions so that the number density of chondrules, n_c, would not change significantly as the system evolved. This is valid for small concentrations due to the small frequency of collisions but breaks down at higher concentrations of chondrules.

Another way of comparing the two models is shown in Fig. 9, which plots the fraction of single chondrules left in a population after the system evolves as described for Fig. 8. This method is better for comparison because it does not distinguish between chondrule aggregates composed of different numbers of the original chondrules. For low concentrations, the two models agree fairly well but, for concentration factors greater than 10, the Gooding and Keil (1981) model starts to underestimate the number of single chondrules remaining. In other words, at high concentrations (those greater than 10× solar), the Gooding and Keil (1981) model overestimates the number of compound chondrules that would be produced.

Table 1 shows more results of this new collisional model. For different concentration factors, the percentage

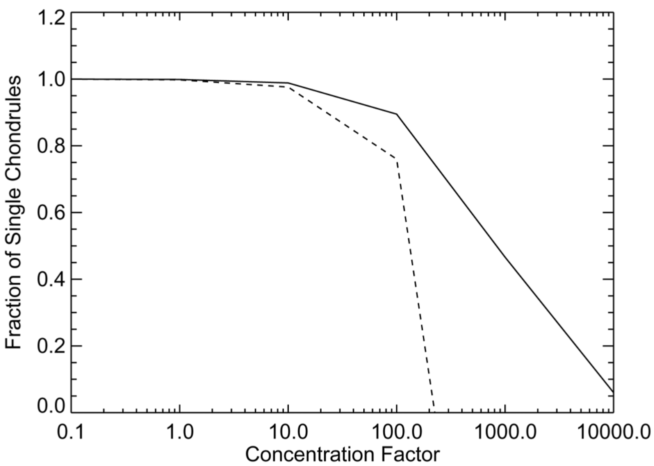

Fig. 9. The fraction of single chondrules remaining for the cases examined in Fig. 8. Our model (solid line) closely matches that of Gooding and Keil (dashed line) for small concentrations but quickly diverges at high concentrations.

Table 1. Frequency of chondrule agglomerates after 10,000 sec of collisional evolution.

Concentration factor	Single	Double	Triple	Quadruple
1	99.88%	0.12	0.00	0.00
10	98.84	1.15	0.01	0.00
20	97.70	2.24	0.06	0.00
30	96.60	3.28	0.12	0.00
40	95.51	4.27	0.28	0.01
50	94.45	5.21	0.32	0.02
60	93.41	6.11	0.44	0.03
70	92.40	6.96	0.58	0.05
80	91.41	7.78	0.73	0.07
90	90.44	8.56	0.89	0.10
100	89.49	9.30	1.07	0.13

distribution of single, double, triple, and quadruple chondrules are listed. The percentages are defined as the number of objects composed of the corresponding number of individual chondrules divided by the number of agglomerates in a given volume. Thus, a double chondrule is counted as a solitary double not as two chondrules compounded together. The initial conditions in these simulations were the same as those described above. For 5% of all chondrules to be compounds, the concentration of chondrules must have been equivalent to a solids-to-gas ratio of approximately 45 times the solar value (though, if Wasson et al. (1995) are correct that only sibling compounds formed via collisions, the concentration factor would be ~25).

How these values would change if all the chondrules were not initially the same size remains to be investigated. For cases with concentration factors above the canonical solar case, a small percentage of agglomerates will contain three or more of the original single chondrules. Thus, compound chondrules are not limited to just two chondrules fused together in the collisional model.

REQUIREMENTS FOR STICKING IN CHONDRULE COLLISIONS

The conditions needed for chondrules to stick upon collisions have not been studied in detail. Connolly et al. (1994) were able to create synthetic compounds, similar to those found in chondritic meteorites, through the collision of chondrules at temperatures between 1300 and 1800 K. We take these results to support our assumption that collisions among chondrules can lead to compound chondrule formation at temperatures above 1400 K. In this section, we present a rough calculation to further test this idea.

The Maxwell time of a substance is a measure of how that substance will respond to an applied stress over some time interval (e.g., Landau and Lifshitz 1970). If the stress is applied over a time period that is less than the Maxwell time, the substance will behave elastically. If the stress is applied over a time period that is longer than the Maxwell time, the substance will react viscously (flow) in response to the applied stress. The Maxwell time is given by:

$$\tau_M = \frac{\eta}{\mu} \quad (29)$$

where η is the viscosity of the substance, and μ is the shear modulus. When chondrules have significant amounts of melt, it is not difficult to imagine that they will behave viscously. However, as their temperatures approach the solidus, their solid content will increase, and they may be more likely to exhibit elastic behavior.

The timescale of interest in the collision of chondrules is the amount of time that the two chondrules would be in contact. A lower limit of this time can be calculated using the Hertzian contact theory (Landau and Lifshitz 1970). This assumes that the two chondrules are spheres before coming into contact and that they behave completely elastically (energy is conserved). The time that the two spheres are in contact is given by:

$$t_{coll} = 2.87\left(\frac{m_1 m_2}{m_1 + m_2}\right)^{\frac{2}{5}}\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{\frac{2}{5}}\left(\frac{r_1 + r_2}{r_1 r_2}\right)^{\frac{1}{5}} v^{\frac{-1}{5}} \quad (30)$$

where the subscripts *1* and *2* represent the different spheres, *m* is the mass, ν is the Poisson ratio of the substance, *E* is the Young's modulus of the substance (which does not vary significantly with temperature), *r* is the radius of the sphere, and *v* is the relative velocity of the two spheres. The shear modulus of a substance can be related to the Young's modulus and Poisson's ratio by:

$$\mu = \frac{E}{2(1+\nu)} \quad (31)$$

Thus, if $t_{coll} > \tau_M$, the chondrules will behave viscously during the time of the collision and stick. If $t_{coll} < \tau_M$, then they will behave elastically and bounce off of one another.

Assuming that the chondrules are made out of materials with similar properties (Young's modulus of 10^{11} Pa, Poisson's ratio of 0.25, and density of 3 g cm^{-3}) to basalt (Turcotte and Schubert 1992) (basalt was also used as a chondrule analogue in Susa and Nakamoto [2002]), we find that the t_{coll} for two 0.3 mm radius chondrules moving with a relative velocity of 1 m/s is 3×10^{-6} sec. Therefore, sticking will occur if the viscosity of the chondrule is less than $(3 \times 10^{-6})\mu$. The shear modulus for basalt is 4×10^{10} Pa based on the numbers used here. Thus, sticking will occur as long as the viscosity of the chondrule is less than 1.2×10^5 Pa s. This viscosity is over two orders of magnitude greater than the viscosities of basaltic flows on Earth at ~1400 K (Fagents and Greeley 2001).

Admittedly, this is only a rough calculation, assuming that the relative velocity of the two chondrules is along their line of centers. However, it does illustrate that sticking can occur even at relatively high viscosities. Viscosities are highly temperature dependent, and a quantitative study of chondrule viscosity at various temperatures is needed. However, we feel that this calculation, along with the results of Connolly et al. (1994) support our assumption that compound chondrules can form at temperatures as low as 1400 K. If compounds can only form at higher temperatures than we have assumed here, it would be implied that t_{plas} is shorter than assumed in the model results presented above. The implications for a smaller value of t_{plas} are discussed below.

DISCUSSION

In deriving the formula for the probability of identifying an adhering compound chondrule in thin sections, a success was defined as when the thin section cut through the projected length of the contact between the two components. We note that if the thin section was cut through the same compound chondrule nearly perpendicular to the line of centers such that it passed through the compound where the secondary chondrule was in contact with the primary, as shown in Fig. 10, it could also be identified as a compound chondrule. However, if this were the case, the thin section slice would make it appear as an enveloping chondrule not an adhering one. The probability of this is low, particularly for small contact arcs, but only a tiny fraction (7.5%) of those compound chondrules identified in a thin section by Wasson et al. (1995) were of this type. Therefore, it could be possible that some, if not all, enveloping chondrules identified in a thin section do not come from compounds in which one chondrule surrounds another but, rather, from adhering compounds that were sliced in a manner such that the primary appears surrounded by the secondary. Statistics of enveloping chondrules from whole chondrules removed from meteorites are needed to further investigate this possibility. This same uncertainty of how a compound is cut by a thin section may cause the apparent diameters of the primaries and secondaries to appear smaller than they actually are, affecting the observed value of r. As noted above, detailed studies of the true values of r are needed to fully understand the histories of compound chondrules.

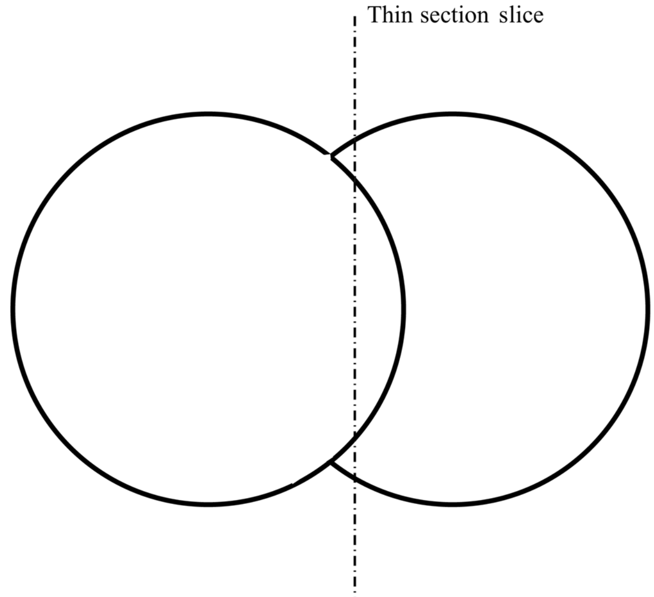

Fig. 10. A possible manner by which an adhering compound chondrule would be sliced by a thin section. If cut in this manner, the compound could be mistakenly identified as an enveloping compound.

If not all compound chondrules formed by the collisions of plastic chondrules, but rather, some formed by the melting of loose aggregates on the surface of a primary chondrule as proposed by Wasson et al. (1995), then the results of this work can still provide some insight into the nebular environment at the time of their formation. Firstly, the higher frequency of compound chondrules suggests that those that formed via collisions (siblings) formed in regions of higher densities of chondrule precursors where, on average, chondrules were concentrated at least 25 times above the canonical solar value. Secondly, the higher frequency of independents (3% here as opposed to 1.4% in Wasson et al. [1995]) implies that more chondrules would have accreted porous aggregates between chondrule forming events than previously believed.

If all compound chondrules are the result of collisions among plastic chondrules, much can be inferred about the environment in which chondrules formed and also the mechanism by which they formed. For example, in the context of the shock model for chondrule formation, the cooling rates for chondrules behind shock waves were found to be greater for higher concentrations of chondrules (Desch and Connolly 2002; Ciesla and Hood 2002). This agrees well with the observation that non-porphyritic chondrules (those that have cooled rapidly) have a higher fraction of compound chondrules than do porphyritic ones. However, this needs to be re-examined because porphyritic chondrules are not believed to melt as completely as non-porphyritic chondrules (Yu and

Hewins 1998). As a result of there being less melt, porphyritic chondrules would likely be more rigid and, therefore, less likely to stick or deform when collisions took place. Such an idea is supported by the data taken by Wasson et al. (1995). The average contact arc in adhering chondrules is significantly smaller when the secondary has a porphyritic texture. Also, of the 15 compound chondrules observed in which one of the adhering components is porphyritic and the other is not, the secondary is non-porphyritic in 11 of them. These two observations suggest that porphyritic chondrules do not deform as easily as non-porphyritic chondrules. Therefore, it is possible that some porphyritic chondrules may have experienced collisions but did not form compounds. If this were the case, porphyritic chondrules may have experienced more collisions than compound chondrule statistics would suggest.

If no difference exists in the abilities of porphyritic and non-porphyritic chondrules to form compounds through collisions, then the discrepancy between the frequency of compound chondrules with non-porphyritic textures and those with porphyritic ones would provide information about how chondrules were formed. Specifically, if, as described above, 71% of all compound chondrules are NN, then 3.5% (71% of 5%) of all chondrules are NN compounds. According to Gooding and Keil (1981), 16% of all chondrules are non-porphyritic. Therefore, ~22% of all non-porphyritic chondrules are compounds. Based on the collisional model developed above, this would require non-porphyritic chondrules to form in regions of the nebula where chondrules were concentrated, on average, 200 times above the solar value. Likewise, if 4% of all compound chondrules are PP, then 0.2% of all chondrules are PP compounds. Because 84% of all chondrules are porphyritic (Gooding and Keil 1981) 0.23% of all porphyritic chondrules are compounds, implying that they formed in regions of the nebula where chondrules were concentrated, on average, at about the canonical solar value.

It is important to note that 25% of all compound chondrules (1.3% of all chondrules) have both porphyritic and non-porphyritic textures in their components. The textures of chondrules are representative of their thermal histories. Therefore, if these compound chondrules were formed by the collision of individual chondrules, those individual chondrules reached different peak temperatures and/or cooled at different rates. This could be achieved in two different ways: 1) the chondrules formed in different heating events, and the secondary formed in a region of the nebula in close proximity to cooler chondrules such that it could collide with one while still plastic; or 2) the chondrules were formed in the same heating event, and the differences in textures are due to differences in how they were thermally processed or different physical properties of the precursors. Those models that have produced thermal histories of silicate particles consistent with those inferred with chondrules (Iida et al. 2001; Desch and Connolly 2002; Ciesla and Hood 2002; Ciesla et al. 2003) require very large formation regions of chondrules, which suggests that the first possibility is not likely. However, we must point out that the shock waves in these models produce a single thermal history for the particles and, therefore, predict that all the chondrules formed in a shock wave would have the same or similar textures. Investigation of how different chondrule textures can be formed in the same heating event are needed. This could be due to spatially varying concentrations of chondrule precursors in the nebula or to attenuation and/or weakening of the heating event with distance from its source. Also, as discussed by Lofgren (1996), different textures can be produced by similar heating if the grain size distribution of the chondrule precursors differed significantly or their chemical compositions were different.

As discussed above, considering the distribution of contact arcs for adhering chondrules in Fig. 7, a preference for small contact arcs (<90°) is strongly noticeable. This is likely due to the fact that most of the secondaries appear smaller than the primaries. A small secondary cannot form a large contact arc (large contact arcs imply high values of r as illustrated in Fig. 1). In fact, an upper limit on the contact arc can be placed for the case when r <1:

$$\varphi_{upper} = 2\sin^{-1}(r) \tag{32}$$

This represents the angle that would be created by an adhering chondrule if the length of the contact, s, was equal to the diameter of the secondary, 2b. Any contact angle is possible for r >1. For r = 0.25, as considered above and as found by Wasson et al. (1995), this gives an upper limit on the contact arc of roughly 30°. Wasson et al. (1995) found some contact arcs that are significantly larger than the upper limit that would be expected based on this formula. Again, uncertainties in where the thin section sliced through the compound could play a role. This could also be due to slight differences in how the radius of the secondary is defined in these two studies (this study is limited to the case of quasi-spherical secondaries). A more detailed investigation into how non-spherical geometries affect these statistics is needed. These effects are likely only important for large deviations from sphericity (large contact arcs with small r), which make up a small fraction of the compounds observed.

If it is true that secondaries tend to be smaller than primaries in compound chondrules, it could imply that smaller chondrules deformed more easily (were hotter) at the time of collision. This could mean that the chondrule formation events kept smaller chondrules hotter for longer periods of time. This issue was addressed by Liffman and Brown (1996) in the context of forming chondrules in protostellar jets. However, as discussed above, compounds with r <1 are more likely to be observed in thin section than compounds with r >1. Thus, more work is needed to understand the distribution of r among compound chondrules.

The preference for small contact angles could also be a result of non-linear cooling (cf., Yu and Hewins 1998). Chondrules will deform most easily during collisions when they have low viscosity, which would correspond to when they are at higher temperatures. At lower temperatures, the deformation would be less and would result in lower contact angles. If chondrules cool non-linearly, the chondrules will spend more time (and experience more collisions) at their lower temperatures (and, thus, at a more viscous state). Thus, the distribution in Fig. 7 could just be a result of this non-linear cooling. Non-linear cooling has been predicted explicitly if chondrules formed by shock waves (Desch and Connolly 2002; Ciesla and Hood 2002), and the preference for small angles would be enhanced if the chondrules become spatially concentrated with time, as described by Ciesla and Hood (2002). The detailed cooling histories of other chondrule formation mechanisms remain to be studied, but they must be able to explain the preference for small contact angles among compound chondrules.

The result that 5% of chondrules are compounds implies that chondrules formed, on average, in regions of the nebula where chondrules were more concentrated than previously believed. Based on the model presented in this study, the average concentration of particles was ~45 times greater than expected for those conditions behind a shock wave in the canonical solar nebula. This number could prove to be conservatively low because it was assumed that all solids were in the form of chondrules. If some fraction of the mass of solids was present as dust in addition to chondrules, as is expected (Hood and Ciesla 2001), or if the mass density of chondrules is higher than the assumed 3 g cm^{-3}, a higher concentration factor would be needed. For example, using the numbers of Desch and Connolly (2002), who assumed that 75% of the solids existed as chondrules and the density of the chondrules was 3.3 g cm^{-3}, the average concentration factor would be ~60 rather than 15, as found by those authors. Likewise, if the sticking efficiency of plastic chondrules is less than 1, as might be expected as chondrules cool and become more rigid, or if the time that chondrules are plastic is less than 10^4 sec, then a larger concentration of chondrules would be required.

Models for chondrule formation other than the shock model would need to enhance solids to much higher relative concentrations. This is because, in a canonical nebula, the ratio of the mass density of solids to the mass density of the gas is a constant (~0.005 above the ice condensation point). If the gas is not compressed by a shock wave, then the relative concentrations of solids must be increased to have the same number density as those used here. Thus, if chondrule formation took place in a region of the nebula with $\rho_g = 10^{-9}$ g cm^{-3} (thought to be typical for ~2.5 AU during the chondrule formation epoch of the solar nebula), chondrules would have to be concentrated, on average, by a factor of 450 to have 5% of all chondrules be compounds. Again, if the plasticity time is less than 10^4 sec, chondrules would have to be concentrated at even higher values. Such large enhancements would be difficult to achieve in the nebula (Weidenschilling 2002). If Wasson et al. (1995) are correct that only some (60%) of all compounds formed via collisions, this still would require shock waves to form chondrules where they were concentrated by at least a factor of 25 and at least 250 if formed by another mechanism.

Many mechanisms have been suggested for concentrating solids in the solar nebula. Among them are turbulent concentration, gravitational settling to the midplane, and collisional disruption of planetesimals (cf., Hood and Ciesla 2001). The latter mechanism has not been studied quantitatively, so expected concentrations produced in this way are unknown. Desch and Connolly (2002) found that the compound chondrule population matches well with the predicted time that particles spend in turbulent concentrations according to Cuzzi et al. (2001). However, these authors argued that chondrules formed in areas of the nebula with an average concentration factor of 15, based on a compound chondrule population of 2.4% not 5%. The average concentration factor of 45 found by this study could still result from turbulent concentrations; however, as mentioned above, this is likely only a lower limit. If the average concentration factor is much higher, this could be the result of gravitational settling to the midplane.

CONCLUSIONS

Thin section studies of compound chondrules have been performed by previous authors, though interpreting what they imply for chondrule formation has been difficult. The uncertainty in where the thin section cut intersects the compound can lead to possible misinterpretation of what the three-dimensional object looks like. Simple geometric models were used to correct for this uncertainty and were applied to previous thin section studies. These corrections showed that compound chondrules may be more common than previously believed and that compounds with secondaries that are large compared to the primaries may also be more common than previously thought. This study provides some clues as to what remains to be learned and how this data must be fit into our models of chondrule formation. The results of this study depend strongly on the detailed data of Wasson et al. (1995). Future thin section investigations of compound chondrules should be as comprehensive as the study carried out by those authors to maximize the information that can be deduced. Future studies using techniques such as X-ray tomography may allow further study of compound chondrules without being subject to the biases and uncertainties inherent with those of thin sections (Hertz et al. 2003).

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