Are Some Chondrule Rims Formed by Impact Processes?
Observations and Experiments

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Observations and experimental evidence are presented to support the hypothesis that high-speed impact into a parent body regolith can best explain certain textures and compositions observed for rims on some chondrules. A study of 19 interclastic rimmed chondrules in the Weston (H 3/4) ordinary chondrite shows that two main rim types are present on porphyritic olivine-pyroxene (POP) and porphyritic pyroxene (PP) chondrules: granular and opaque rims. Granular rims are composed of welded, fine-grained host chondrule fragments. Bulk compositions of granular rims vary among chondrules, but each rim is compositionally dependent on that of the host chondrule. Opaque rims are composed of fine-grained, host chondrule fragments. Bulk compositions of opaque rims vary among chondrules, but each rim is compositionally dependent on that of the host chondrule. Opaque rims contain mineral and glass compositions distinctly different from those of the host, partially reacted chondrule mantle components, and some matrix grains. Opaque rims are greatly enriched in FeO (up to 63 wt%). The original chondrule pyroxene composi-

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temporarily melted projectile. These experimental results demonstrate that rim-like thermal and mechanical alteration of projectiles can result from a high-velocity encounter with a low-density target. Therefore, experiments using appropriately chosen projectile and target materials can provide a test of the hypothesis that chondrule rims common to Weston and possibly other ordinary chondrites were formed by such a process. © 1991 Academic Press, Inc.

I. INTRODUCTION

There is considerable evidence that chondrules were not formed in connection with planetary processes, but rather were formed in the early solar nebula (Grossman 1988 and references within). However, it is not clear in what environment the fine-grained rims, common on many chondrules, formed (e.g., Christophe Michel-Levy 1976, Ashworth 1977, Allen et al. 1980, King and King 1981, Matsunami 1984, Grossman and Wasson 1987, Alexander et al. 1989b). Fine-grained rims have been compared to matrix-like material, and have also been observed on nonchondritic objects and clasts in ordinary chondrites (OC) and in some carbonaceous chondrite (CV) meteorites (Scott et al. 1984). Hypotheses regarding the formation of rims must confront a complex set of observations regarding the relationships between rims, chondrules, and matrix. Whereas many rim bulk compositions resemble their respective meteorite matrix, different rims from the same chondrite can have very different compositions (Scott et al. 1984). Moreover, some rims are cataclastic equivalents, in terms of composition and mineralogy, of the bulk chondrule. Why do some chondrule rims, e.g., Semarkona, have enhanced siderophile and chalcophile contents relative to their respective interiors (Grossman and Wasson 1987)? Is the compositional zoning (interior to margin), which is commonly observed in chondrules (Jones and Scott 1989), related to chondrule formation or postformational processes? What correlations, if any, exist between rim composition and rim texture? Cursory examination of unequilibrated ordinary chondrites (UOCs) shows that some of these meteorites contain many intact chondrules, very little fragmental material, and very little fine-grained matrix (e.g., Semarkona) while others have intact chondrules, many fragmented chondrules, and variable amounts of fine-grained matrix (e.g., Weston). Can all of these characteristics be reconciled with nebular formation, or are parent body processes also involved in some cases?

Little attention has been paid to possible mechanical and thermal modifications of accreting particles as they strike low-density regoliths of meteorite parent bodies. Particles that survive accretion onto a parent body at rather high velocities (> 1 km sec⁻¹) might be expected to undergo such modification. We have started a series of experiments (Bunch et al. 1990) using the Ames two-stage vertical light gas gun (LGG) to accelerate particles in the range of 1–6 km sec⁻¹ into underdense foam (aerogel; ρ = 0.05–0.1 g cm⁻³) and fine-grained particulate targets. The primary objective of this investigation is to determine the effects of high-velocity impacts on silicate projectiles and ascertain if these effects have any relationship to characteristics observed for chondrule rims.

II. METEORITE OBSERVATIONS

Rims around chondrules have been observed as early as the time of Tschermak (1885), who noted that chondrules were enclosed by thin "shells" rich in iron and sulfides. Many types of rims have been observed and described on UOC chondrules and on chondrules in other chondritic classes. Fine-grained, Fe-rich rims (Allen et al. 1980, Huss et al. 1981), "dark-zoned chondrules" (Dodd and Van Schmus 1971) or "coarse-grained lumps" (Rubin 1984) and coarse-grained rims (Rubin 1984) have been reported. "Accretionary rims" are particularly common in CM and CV3 chondrites (Metcalf et al. 1988). Rims on UOC chondrules are quite variable in texture and composition. Allen et al. (1980) refer to rims as "chaotically heterogeneous." Matsunami (1984) reported textural and compositional differences between rims and matrix and from chondrule to chondrule. Scott et al. (1984) also found no particular relationship between "matrix rims" and host chondrules. Here we describe rims found on Weston chondrules whose characteristics suggest a particular mechanism of rim formation, testable by experiments.

The present investigation relied on the following procedures. Three thin sections of the Weston regolith breccia meteorite (H 3-4) were studied with a petrographic microscope followed by scanning electron microprobe analyses and back-scattered electron (BSE) imaging of selected chondrules. The analyses were performed on a Cameca MBX scanning electron microprobe, using an accelerating potential of 15 kV, a beam current of 20 nA, and counting times of 60 sec. Final analyses were obtained after applying ZAF (atomic number, mass absorption, fluorescence) correction procedures. Bulk compositions of chondrule components were obtained by broad-beam (rastered) microprobe analysis, following the procedures of Lux et al. (1980). Weston was chosen for this study because an adequate reference data base has been established from many research disciplines and because it exemplifies the types of features that we are trying to explain by high-speed impact processes. Although Weston is a regolith breccia containing clasts of other chondrites, the interclastic chondrules characterized in this study, as well as the surrounding matrix, appear to have sustained only slight solid-state recrystallization (metamorphism) since rim formation, a characteristic feature noted by Ashworth (1977) during a TEM study of Weston matrix.
Results of a thin section survey on 4 cm² of Weston show that this chondrite has an average of 18 mostly intact interclastic chondrules per square centimeter. The most common primary textural type is porphyritic olivine–pyroxene (POP) followed by porphyritic olivine (PO), porphyritic pyroxene (PP), and barred olivine (BO), which together combine for 91% of the textural types (four other minor types are also present). This is in good agreement with the data of Gooding and Keil (1981) for Weston and other ordinary chondrites. We find that 34% of POP chondrules, 30% of PO chondrules, 18% of PP chondrules, and 0% of BO chondrules are completely rimmed. Gooding and Keil (1981) found somewhat lower abundances of rimmed chondrules in their study of Weston. In addition, many partially rimmed chondrules are present for each type; portions of the rims appear to have been lost. The average diameter of intact chondrules is ~0.52 mm (range = 0.09–1.1 mm), whereas the mean matrix fragment size is 0.038 mm (range <0.005–1 mm), although most of the matrix fragments are <0.038 mm. Thus chondrules, on the average, are at least 14 times larger than surrounding cataclastic matrix fragments.

Examples of intact chondrules are shown in Fig. 1. We classify the observed rims into two types; both are variable in terms of composition and texture from one rim to another. (1) Granular rims, which are ~0.02–0.04 mm thick, contain small (submicrometer to 12 μm) mostly equant grains, whose compositions are very similar to the phases within the host chondrule and, more specifically, to the phases within ~0.04 mm of the rim boundary (Figs. 1a–d), which we call the mantle. These rims have a sintered appearance, but do not show classic recrystallization textures. Opaque rims (referred to as fine-grained, Fe-rich rims by Allen et al. (1980) and Huss et al. (1981), which are ~0.009–0.03 mm thick, contain very small (submicrometer to 3 μm) grains of Fe-rich olivine, sulfides, NiFe metal, unidentified phases, fragments of chondrule mantle phases, and a minor contribution from the matrix (Figs. 1e and f). Of the 19 interclastic chondrules that we studied in Weston, 11 are fine-grained, Fe-rich or opaque type, 5 are granular, and 2 are unclassified. An ongoing independent study of chondrule rims in UOC L-group meteorites (ALH 85070, ALHA 78119 and LEW 86505; petrographic types 3.4, 3.5, and 3.6 respectively) show that of 179 intact chondrules >0.7 mm, 134 or 75% have rims. Of these, 72% are fine-grained, Fe-rich (opaque), 10% are coarse-grained, 10% are granular, 4% resemble dark-zoned chondrules, and the remainder are unclassified.

Electron microprobe analyses of individual phases in and bulk compositions of rims, mantles, and cores (unaltered primary phases) of the chondrules shown in Fig. 1 are given in Tables I and II and partially illustrated in Fig. 2. Phase analyses of POP(G) (G = granular rim) show compositional zoning from core to mantle to rim for FeO, MgO, Na₂O, and K₂O. With the exception of these oxides, only subtle differences exist among corresponding phases in the core, mantle, and rim. Bulk analyses (Table II) do not reflect zoning for FeO, which can be attributed to the enhanced troilite content in the core. Bulk analyses also show an increase in Al₂O₃ and CaO contents from the core to the mantle, which is probably due to observed higher glass and Ca–pyroxene contents in the mantle. PO(GF) (GF = granular-fritted) is composed of a much simpler mineralogy, essentially olivine and glass (mesostasis) with minor amounts of Ca–pyroxene, FeS, and NiFe. These also show zoning among the phases from core to rim; however, few compositional trends are apparent in comparison to bulk compositions (Tables I–II). As is the case for the rim mineralogy in POP(G), phases present are the same as the mantle, with the exception of a few grains of plagioclase, olivine, and pyroxene that are similar in composition to matrix components.

Sample POP(R) is quite different from the granular types in that the rim is extremely enriched in FeO. Most of this chondrule’s NiFe metal and FeS are situated in the mantle and protrude into the rim where they have a dissipated appearance (Fig. 1e); all of the phases in the rim are extremely Fe-rich. In fact, some olivines reach a composition of Fa₈₈. Whereas rim phase compositions in granular rim types have a narrow compositional spread, minerals in POP(R) show considerable range. Olivine in the rim (shown in Fig. 1f) has a range of Fa₈₁ to Fa₇₂; low-Ca pyroxene (cpx) in the mantle has an FeO content of 3.2 to 5.6% at the interface; Ca–pyroxene (cpx) in the rim has an FeO range of 7.4 to 15.4%. High contents of Al₂O₃ and Na₂O in mantle and rim phases are also noted. NiFe metal composition is almost constant at Ni = 4.8–5.1%. Matrix phase (mostly olivine, Fow₂₀₋₇₀, anorthite, and mesostases) and bulk compositions adjacent to all of the above rims are dissimilar in composition to those of the rims. PP(R) is similar to POP(R) in that it has an Fe-rich reaction-like rim, although its bulk and phase characteristics are different. The sample appears to be a broken portion of a large chondrule that has one curved surface overlain with a fayalite rim (Fig. 3). It consists predominantly of euhedral hypersthene crystals, whose basal and (010) sections show narrow bands of concentric compositional zoning (Fig. 3). Cores have a composition of Fs₃₂, which is surrounded by a reverse zone of Fs₉₈, followed by continuous zoning to the grain margin of Fs₄₃. The margins are also enriched in Al₂O₃ (2.42%), Na₂O (0.70%), and CaO (4.7%). Mesostasis consists of three components: (1) SiO₂, (2) SiO₂–Al₂O₃, and Al₂O₃–FeO–rich, and (3) FeO–rich (see Table I). Minor amounts of taenite (Fe = 56.4, Ni = 44.2%), troilite, (Fe = 62.1, S = 37.7%), and small quench crystals of fayalite (Faₙ₉₈) are present in association with the mesostasis. These fayalite crystals have no association with rim fayalite formation; they, together with
FIG. 1. SEM-BSE images of rimmed chondrules in Weston. (a) Partial POP(G) chondrule with a granular rim (arrow). (b) Enlarged view of rim. (c) POP(GF) chondrule with a granular-fritted rim that partially surrounds the chondrule. (d) Enlarged view of rim in c; Dark grains in the rim and mantle are glass of similar composition and lighter grains in the rim and mantle are olivine or similar composition (Table 1). (e) POP(R) chondrule with an Fe-rich olivine and NiFe metal-rich opaque rim (arrows). (f) Enlarged view of rim in e. Scale bars for a, c, and e = 0.1 mm. Scale bars for b, d, and f = 10 μm.
SiO₂, are fractional crystallization residuum products of the bulk chondrule. Pyroxene zonation patterns and euhedral grain outlines are cut at the chondrule/rim interface, which in effect forms a discontinuity between the end of chondrule formation and rim inception. The rim shows an undulating to sawtoothed relationship with chondrule hypersthene and, in places, a layer of intact fayalite (Fa⁷⁶–⁸⁵) overlies hypersthene (Fig. 3). Most of this fayalite...
These physical and mineralogical characteristics are interpreted in the following section in terms of a hypervelocity encounter with a lower-density regolith.

III. INTERPRETATION OF PETROGRAPHIC OBSERVATIONS

Our study of Weston rims identifies two main rim types for POP and PP chondrules: (1) granular rims that appear to be clastic in origin with subsequent sintering (Fig. 1) and (2) opaque rims that show distinctly different phase (minerals and glasses or amorphous phases) compositions compared with the host chondrule and compositional zoning with partially reacted mantle components that are included within the rim.

Granular Rims

These are composed of fine-grained chondrule phase equivalents (Table I) with bulk compositions that are also mostly similar to the host chondrule (Table II, Fig. 2). Granular rim grains do not show a paragenetic sequence as do chondrule interior and mantle phases (Mg-olivine and pyroxenes first, followed by Ca-pyroxene and glass). Instead, they appear to be mechanically derived fragments of the host chondrule together with a few fragments of matrix that were all aggregated together during an abrasive process at submelting temperatures. Any metamorphism sustained by Weston during and/or after consolidation into a coherent rock was insufficient to promote observable textural and compositional effects: grain boundary triple junctions, equilibration of phases, or recrystallization of rim and chondrule glasses. Clearly, the rims are not products of metamorphism during lithification. Nagahara (1984) also concluded that UOC chondrule rims could not be formed by lithification (compression and induration) in the parent body regolith (Rambaldi et al. 1981) because of the dissimilarity in matrix and rim compositions, a conclusion also reached by Matsunami (1984). Furthermore, Nagahara concluded that rim textures are suggestive of the heterogeneous attachment of grains onto already existing chondrules, as opposed to material which formed simultaneously with chondrules. A similar conclusion was reached earlier by Allen et al. (1980), who state that UOC chondrule rim data are inconsistent with the heating mechanisms that formed chondrules. Nagahara (1984) suggested that chondrule rims and matrix material accreted onto chondrules during turbulent nebular conditions, but Weston granular rims are composed of host chondrule phases. If they had accreted from the nebula, they would not be expected to have a correlation with host chondrule compositions. In fact, Alexander et al. (1989b) have made convincing arguments against nebular rim formation. They contend that microm-
TABLE II

Electron Microprobe Bulk Analyses of Rims, Mantles, and Cores of Selected Chondrules in the Weston Chondrite

<table>
<thead>
<tr>
<th>Sample(^a)</th>
<th>SiO(_2)</th>
<th>Al(_2)O(_3)</th>
<th>Cr(_2)O(_3)</th>
<th>TiO(_2)</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na(_2)O</th>
<th>K(_2)O</th>
<th>P(_2)O(_5)</th>
<th>S</th>
<th>Ni</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>POP(G)</td>
<td>Rim</td>
<td>51.6</td>
<td>5.5</td>
<td>0.62</td>
<td>0.20</td>
<td>24.6</td>
<td>3.63</td>
<td>3.38</td>
<td>0.28</td>
<td>0.15</td>
<td>0.35</td>
<td>0.04</td>
<td>100.45</td>
</tr>
<tr>
<td></td>
<td>Mantle</td>
<td>52.2</td>
<td>5.4</td>
<td>0.62</td>
<td>0.18</td>
<td>25.7</td>
<td>3.10</td>
<td>3.5</td>
<td>0.24</td>
<td>0.15</td>
<td>0.50</td>
<td>0.04</td>
<td>100.87</td>
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<td>Core</td>
<td>51.6</td>
<td>2.0</td>
<td>0.72</td>
<td>0.10</td>
<td>10.9</td>
<td>3.10</td>
<td>0.85</td>
<td>0.05</td>
<td>0.03</td>
<td>1.8</td>
<td>0.04</td>
<td>100.22</td>
</tr>
<tr>
<td>PO(GF)</td>
<td>Rim</td>
<td>47.8</td>
<td>4.6</td>
<td>0.40</td>
<td>0.15</td>
<td>14.4</td>
<td>27.1</td>
<td>2.10</td>
<td>2.68</td>
<td>0.41</td>
<td>0.59</td>
<td>0.31</td>
<td>&lt;0.02</td>
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<tr>
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<td>46.1</td>
<td>4.5</td>
<td>0.59</td>
<td>0.17</td>
<td>15.0</td>
<td>26.8</td>
<td>3.30</td>
<td>2.76</td>
<td>0.22</td>
<td>0.43</td>
<td>0.68</td>
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</tr>
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<td>47.3</td>
<td>4.0</td>
<td>0.63</td>
<td>0.13</td>
<td>14.1</td>
<td>28.0</td>
<td>3.35</td>
<td>2.10</td>
<td>0.35</td>
<td>0.05</td>
<td>0.30</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>POP(R)</td>
<td>Rim</td>
<td>31.9</td>
<td>0.84</td>
<td>0.20</td>
<td>0.05</td>
<td>52.0</td>
<td>11.6</td>
<td>0.39</td>
<td>0.65</td>
<td>0.11</td>
<td>0.33</td>
<td>0.12</td>
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<tr>
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<td>Mantle</td>
<td>53.8</td>
<td>1.33</td>
<td>0.59</td>
<td>0.08</td>
<td>15.1</td>
<td>25.2</td>
<td>1.82</td>
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<td>0.13</td>
<td>0.27</td>
<td>0.15</td>
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<td>Core</td>
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<td>5.3</td>
<td>0.72</td>
<td>0.20</td>
<td>4.2</td>
<td>34.2</td>
<td>3.02</td>
<td>2.82</td>
<td>0.05</td>
<td>&lt;0.02</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>PP(R)</td>
<td>Rim</td>
<td>37.4</td>
<td>1.88</td>
<td>0.38</td>
<td>0.08</td>
<td>44.3</td>
<td>13.0</td>
<td>1.49</td>
<td>0.41</td>
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<td>0.07</td>
<td>0.08</td>
<td>0.16</td>
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<tr>
<td></td>
<td>Core</td>
<td>51.5</td>
<td>1.97</td>
<td>0.53</td>
<td>0.08</td>
<td>24.4</td>
<td>19.1</td>
<td>1.54</td>
<td>0.72</td>
<td>0.04</td>
<td>0.06</td>
<td>0.12</td>
<td>0.10</td>
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</table>

\(a\) POP(G), porphyritic olivine–pyroxene (granular); PO(GF), porphyritic olivine (granular–fritted); POP(R), porphyritic olivine–pyroxene (reaction); PP(R), porphyritic pyroxene (reaction).

Note. Analyses of rims and mantles were made by beam-rastering on fifteen 10 \(\times\) 10-\(\mu\)m areas; cores analyses were made on 100 \(\times\) 100-\(\mu\)m areas.

opaque-sized clastic grains could not have remained unreacted with ambient gas during cooling on a nebular time scale. In addition, they argue that rim grains as a nebular condensate do not have an unfractored chondritic chemical compositions. We know of no way to produce these rims by either igneous or condensation processes. We conclude that these granular rims formed by mechanical abrasion, under subsolidus temperatures, possibly during penetration through a low-density, unconsolidated surface regolith.

**Opaque Rims**

Petrographic observations of opaque rims of POP(R) and PP(R) show four important petrogenetic characteristics. (1) Parts of the mantle appear to have been dislodged into the rim and reacted with material in the rim during and/or after rim formation. (2) Many parts of the mantle, which border the rim (interface zone), have compositions intermediate between those of the Mg-rich chondrule mantle and the Fe-rich rim (Table II). This strongly implies a high-temperature environment and rapid rim formation. (3) The cutting of euhedral crystals and concentric zonation patterns at the chondrule/rim interface (Fig. 3) imply an "erosional" period before rim formation. This "erosional" feature has also been observed by Kitamura and Watanabe (1986) and Dodd (1981) in other chondrites. (4) Distribution of Al in rims can be accounted for by redistribution from the host into the rim phases during melting. In addition, reaction rims are greatly enriched in FeO and are not similar in either phase or bulk compositions to host chondrules (Tables I and II). The rim material apparently reacted with included host fragments and the interface region between the rim and the mantle. The latter is characterized by enhanced FeO near the reaction surface, decreasing with distance away from the reaction surface. Most of these areas were disrupted during and/or after rim formation. A metamorphic origin is precluded by the observation that compositional inhomogeneities of particles in the rim, igneous compositional zoning in host hypersthene, and the presence of glasses with compositional heterogeneities in both rim and host would have been greatly modified or lost during a metamorphic event.

How did such Fe-rich olivine crystallize onto the chondrule surface and what promoted the reactions? The formation of fayalitic olivine (<Fos0) from FeO and enstatite alone is unattainable, unless free SiO\(_2\) exists in the system (Nagahara 1984, Nagahara and Kushiro 1987). Nagahara
and Kushiro (1987) found from their experiments that Fe-rich olivine (>Fae4) could not have formed from a gas of solar nebula composition by equilibrium condensation without the presence of free silica according to the equation

$$2\text{Fe}(s) + \text{SiO}_2(s\text{ or } g) + \text{O}_2(g) = \text{Fe}_2\text{SiO}_4(s) \quad (1)$$

with $fO_2$ above the IQF (iron–quartz–fayalite) buffer for the reaction to proceed. They considered that fractionation of a silicon-rich gas in the nebula during condensation, together with $fO_2$ values much higher than that of the average solar nebula, was responsible for the formation of ultra-Fe-rich olivine. However, these olivine compositions can be obtained from reactions with Fe-bearing, low-Ca pyroxene and olivine (Nagahara 1984), which are present in the host chondrules’ mantles. Alexander et al. (1989b), discounting a nebular origin for the fayalite, devised a process whereby fragmented silica-rich chondrule mesotases reacted with oxidized Fe from metal and Na (and also Al) to form groundmass rims of fayalite and feldspathic “glue.” Our analyses (Tables I and II) and observations (Fig. 3) support this hypothesis and, furthermore, suggest that the fragmentation and reaction events occurred during impact penetration into the regolith. Fragmentation and melting of chondrule margins could have produced the components necessary for the groundmass “glue.” Our observations show fragmented chondrule remnants in Fe-rich rims and the mechanical and possibly thermal degradation of chondrule surface NiFe metal and sulfides. Many rimmed chondrules clearly show the involvement of the outer one-half of metal and sulfide nodules, which either are missing or are distributed as granular fragments in the nearby rim; the chondrule facing sides of the original nodules are mostly intact. These minerals served as the source of Fe for Eq. (1); SiO$_2$ and O$_2$ were contributed from the melting and vaporization of chondrule silicates and silica-rich glass. The “feldspathic glue” may have been derived from the melting of Al-rich, alkalic-rich chondrule mesotases. Compared with Mg-rich precursors in POP(R) chondrites, the case is much easier for PP(R) (Table II, Fig. 3) where the starting material for fayalite was an Fe-rich pyroxene and free silica was available from the mesostasis. Hutchison and Bevan (1983), on the basis of textural evidence, concluded that dark rim material on at least some Tieschitz chondrules and clasts was added when these components were still hot (plastic). From a TEM study of UOC rims, Ashworth (1977) also found evidence of a hot rim–chondrule association and compared the rims to rapidly crystallized melts or glasses. The TEM observations of fused olivine groundmass in the chondrule rims of Sharps (Alexander et al. 1989b) strongly indicate that the olivine and, by association, the rim formed in response to a high-temperature event with insufficient time during cooling to allow for fused olivine crystallization. These observations are difficult to reconcile with a condensation origin.

Opaque and granular rim formation by impact penetration is consistent with (1) an encompassing rim, the fine-grain size, and the thin, but somewhat limited range in rim thickness; (2) rim, mantle, chondrule, and matrix bulk compositional interdependences; and (3) rim, mantle, chondrule, and matrix phase (minerals and glasses) compositional interdependences. Grossman and Wasson (1987) found that fine-grained chondrule rims have enhanced siderophile and chalcophile element contents compared to their respective interiors; K, As, and Zn are particularly enhanced. They concluded that metal and sulfides of both portions formed from a single precursor assemblage, possibly during reheating of the chondrule when droplets of these minerals mixed with accreting matrix-like material to form a surface rim. We agree with their conclusion that chondrule metal and sulfides mixed with fine-grained material to form rims, but we contend for these that the fine-grained material was contributed by fragmentation of the host chondrule admixed with molten and/or fragmented metal and sulfides from the host chondrule rim/mantle interface. From our bulk analyses of chondrule mantles and rims (Table II), the enrichment or depletion of elements in the rim is related to their distributions within the chondrule. Most chondrules are not homogeneous; there are compositional zoning patterns from core to the margins. Table II shows that during chondrule formation, certain elements were enriched or depleted in mantles relative to the interiors, which is at least partially dependent on mineral and glass distribution within the entire chondrule (Table I). The more Fe-rich components tend to be located in the mantle so that when the chondrule is abraded by impact penetration into the regolith, the outer phases are those that are preferentially fragmented to form the rim. Some matrix grains may be mixed into the rim, which adds to compositional heterogeneities.

Two other data sets are relevant to the formation of rims: oxygen isotope signatures and the irradiation record. Clayton et al. (1986) found oxygen isotopic heterogeneities within the ordinary chondrite group according to chondrule size and classification. Measurements of Semarkona and Allan Hills 76004 matrices gave discordant results with respect to the association of chondrules and matrix, with chondrules being relatively enriched in $^{16}$O. Rubin et al. (1990) made oxygen isotopic analyses on Allende chondrules, their rims, and matrix. Their results indicate that the chondrules formed in a high-temperature, $^{16}$O-rich, refractory lithophile and alkali-rich environment, relative to their rims, which formed in a lower-temperature, $^{16}$O-poorer, environment enriched in FeO and volatile siderophiles. Meteoritic matrices are Fe-rich
and $^{16}$O-poor relative to chondrules. If the Allende $^{16}$O isotopic rim patterns are found to be similar to Weston reaction patterns, then simple mixing during impact melting of both matrix and chondrule could account for the isotopic rim signatures, which are mostly intermediate between chondrules and their respective matrices in oxygen isotopic contents and also in Fe.

There is little information on the irradiation record of chondrules and their rims, but that which exists is consistent with the proposed model. Housten and Wilkening (1982) concluded that the solar flare irradiation record of chondrites more closely approximates a "planetary state" than a "nebular state" of exposure, although the low track abundance could be explained by shielding effects of high densities of chondrules and dust during postformational residency times in free space. Allen et al. (1980), in a study of chondrules from five UOC samples, found no evidence from their irradiation track records to support "long-term" existence in space as individual entities. Rim formation upon impact would erase previous irradiation records in the rim.

Matrix

Arguments for UOC matrix origin reduce to "nebular" versus "parent body" scenarios. Until recently, UOC matrices were thought to have formed as low-temperature condensates from the solar nebula (Larimer and Anders 1970, Huss et al. 1981, Nagahara 1984). Rambaldi et al. (1981) described UOC matrices as being composed of highly disequilibrated constituents. Olivine content in the matrices ranges from Fo$_{100}$ to Fo$_{10}$, whereas chondrule olivine compositions range from Fo$_{100}$ to Fo$_{60}$ (Nagahara 1984). Since the chondrule olivine compositional range does not cover that of the matrix, this has led some investigators to suggest that the matrix was not derived from chondrules and that a higher degree of fractional condensation under conditions more oxidizing than those of a nominal solar nebula were required for the formation of matrix olivine. Although this concept may be valid, alternative mechanisms appear to better explain matrix olivine composition. Iron-rich olivine rims contain fayalitic olivine as Fe-rich as Fa$_{92}$ from our measurements, with a range in Fe content down to Fa$_{45}$. Fragmentation of these rims is adequate to explain the presence of fayalitic olivine in the matrices. Allen et al. (1980) concluded that chondritic matrices are not primary components, but were formed by brecciation and comminution of chondrules and rims. Nagahara (1984) cited two observations that seemed to contradict their conclusion: (1) matrix grains with Fe-rich olivine on cores of magnesian olivine without continuous zoning and other disequilibrium assemblages of olivine and pyroxenes, and (2) small, irregular matrix grains that crystallized from a liquid (some with concentric zoning to the present grain surface), which are different from crystals within chondrules. However, our observations and those of Alexander et al. (1989b) clearly show that disequilibrium assemblages are common in the Fe-rich opaque rims, and that fragmentation of chondrule crystals into small, irregular grains is common in granular rims. Therefore, fragmentation of both opaque and granular rims can easily account for the "unique" nature of matrix grain characteristics observed by Nagahara. Alexander et al. (1989b) also conclude on the basis of EMPA and ATEM observations of UOC rims and matrix that matrices result from chondrule breakup. They also showed that the grain size distribution of Bishunpur matrix conforms to a fragmentation power law consistent with fragmentation of chondrules. Similar size distributions were found by Ashworth (1977) for Chainpur and Weston matrices.

In the following section, we describe preliminary experiments designed to test the feasibility of a regolith impact-rim formation hypothesis.

IV. LIGHT GAS GUN EXPERIMENTS

A. NASA Ames Vertical Gun

This facility permits the launching of projectiles with masses up to 0.3 g to velocities of 3.0 to 6.5 km sec$^{-1}$ with a two-stage light gas gun and from 0.5 to 2.5 km sec$^{-1}$ with a powder charge. The large target chamber accommodates a variety of environments (different gases or levels of vacuum) while an elevating screw allows shots to be fired through seven ports in 15° increments from horizontal to vertical. Spiral grooves (rifling) in the launch tube induce a spin to the projectile and sabot (projectile carrier for transmission through the gun barrel). Upon exiting the launch tube, the sabot and the projectile are separated by centrifugal force. A diaphragm prevents the sabot fragments from continuing downrange. As the projectile interrupts a narrow photobeam at three separate stations, the times are recorded and photographs are made, thereby establishing the integrity and velocity of the projectile. This approach typically requires use of projectiles between 0.159 and 0.6 cm in diameter. However, a technique was developed for launching much smaller sizes for studies of intact capture of hypervelocity projectiles (Tsou et al. 1989, Tsou 1991). Projectile samples were placed within a cup-shaped compartment and covered by an aluminum plate. As the sabot splits, the aluminum cap travels downrange with the cloud of sample particles. Centrifugal force produced by the rifling in the launch tube spreads the particles over an area broader than the leading aluminum cap, which passes through a central opening in the capture stage. The capture stage consists of individual pieces of aerogel placed behind
small apertures encircling the central opening in an Al plate, which allows particles to be captured without disruption by plate impact. The aerogel capture media that collected the 2.2 and 5.6 km sec\(^{-1}\) grains had a density of 0.1 g cm\(^{-3}\).

### B. Recovered Grain Characteristics

Experimental projectiles were recovered from the SiO\(_2\) aerogel targets (\(\rho = 0.1\) g cm\(^{-3}\)), mounted in epoxy, and polished for observational and analytical investigations. Projectiles fired at three different velocities have been analyzed.

1. **2.2 km/sec shot.** Projectiles, consisting of terrestrial forsteritic olivine and glass, pyroxene, and pyrite, were fired into aerogel at 2.2 km sec\(^{-1}\). The average depth of penetration into aerogel was \(\sim 2\) mm (Fig. 4); recovered grains show a reduction in grain diameter from \(\sim 0.2\) mm to an average of 0.06 mm. Petrographic examination shows that no melting or shock damage occurred.

2. **4.7 km/sec shot.** Lunar sample grains (pyroxenes and plagioclase) with preshot diameters of \(\sim 0.2\) mm were recovered from average depths of 0.8 cm and show a variety of projectile--aerogel target characteristics that range from melted aerogel, mixed with projectile fragments, that nearly rims the entire grain (Fig. 5a) to grains that have melted aerogel clumps admixed with partially melted projectile at the trailing edge of the grain (Fig. 5b). The grain in Fig. 5b also shows attached, compressed aerogel along the leading edge of the fired grain. Other grains show mixing of melted and crushed aerogel and projectile along \(\sim 180^\circ\) of the projectile surface (Fig. 5c).
   - The Ca--pyroxene grain shown in Fig. 5a was acid-etched to reveal solar flare track characteristics (Fig. 5d). The results indicate a nearly even distribution of sharply defined tracks except for the area near the surface of the grain where the tracks appear diffuse in definition and may have partly annealed. Electron microprobe analyses along traverses from the apparent center of the grain to the edge show no significant evidence of elemental redistribution. Analyses of fragmented grains within melted aerogel also show no compositional differences outside the bulk grain compositional range.

3. **5.6 km/sec shot.** Recovered grains [same projectiles as in (1)] show a reduction in grain size to an average of \(\sim 0.08\)-mm, melted rims (some admixed with host fragments), which in turn are rimmed by melted and crushed aerogel (Fig. 6). Glass particles in the rim, nearest to the host margin, are depleted in SiO\(_2\) content relative to the host; glass near the aerogel boundary is enriched in SiO\(_2\), which indicates some mixing of aerogel with the rim. The grain size reductions are largely due to grain acceleration and perhaps midrange collisions of the projectile grains as they leave the holding cup. Thus, some of the projectiles have struck the aerogel with reduced mass.

Aerogel rim shapes are highly variable for particles fired in the velocity range 4.7 to 5.6 km sec\(^{-1}\) (Fig. 7). Rims may completely surround the modified particles as shown in Fig. 7a, where the aerogel rim surrounds an inner rim of melted and fragmented olivine; tiny inner rim fragments are detached and included within the aerogel rim. Figure 7b shows a plagioclase particle nearly enclosed by a rim of mostly melted aerogel with some minor contribution of melted plagioclase. Other rims are asymmetrical in that they only partially enclose the particle (Figs. 7c and d); the leading edge is devoid of any rim material. Asymmetrical rims may be due to flow of material toward the trailing edge as the impactor penetrates through the target. Asymmetrical rims are also found in chondritic meteorites; an example is shown in Fig. 7e. Experimental characteristics that are similar to chondrule rims are (1) the granulation of projectile (chondrule analog) and aerogel (matrix analog) and (2) partial melting of projectile and aerogel which, together with granulated target and projectile material, forms a rim around the projectile. This is possibly analogous to the Bishunpur chondrule rims studied by Alexander et al. (1989a), which consist of mineral clasts that were possibly cemented in place by an amorphous "feldspathic glue."

Aerogel targets were chosen to ensure the intact capture of the projectiles; they cannot be considered to be a definitive analog to a parent body regolith. However, the similarities cited above are consistent with the impact hypothesis and are sufficiently encouraging to support further investigations with more appropriate target materials.

### V. THEORETICAL CONSIDERATIONS

The projectiles in the experiments are observed to penetrate the target by displacing a column of material of depth \(d\) and width approximately equal to the particle diameter. If such a projectile survives intact, it will stop when it has encountered a mass approximately equal to its own. For a spherical particle of radius \(a\) and density \(\rho_1\) encountering a medium of constant density \(\rho\), the penetration depth will be

\[
d = \frac{4\rho_1a}{3\rho}
\]

Taking \(\rho = 0.1\) g cm\(^{-3}\), \(a = 0.06\) mm (corresponding to the final radius of the particles in the 2.2 km sec\(^{-1}\) shot), and \(\rho_1 = 3\) g cm\(^{-3}\), we find \(d = 0.24\) mm, very close to the observed average value of 0.2 mm. For the 4.7 km sec\(^{-1}\) shot, \(a = 0.2\) mm, and the penetration depth should increase to 0.8 cm, which is consistent with the experimental results. If the kinetic energy is dissipated along the path of penetration, the time required for complete deceleration is
FIG. 4. Compound microscope photograph of aerogel target block with projectile penetration tracks and projectiles (small open arrows) for 2.2 km sec⁻¹ shot. Longest track = 3 mm, transmitted light. Closed arrow points to particle (olivine) shown in enlarged inset; particle = 0.060 mm.
FIG. 5. Scanning electron microscope images of recovered lunar dust grains fired by the light gas gun into aerogel at 4.7 km sec⁻¹. (a) Ca–pyroxene projectile partially surrounded by fragmented Ca–pyroxene (arrows), which is enclosed by melted aerogel. (b) Lunar grain recovered from its rest position in the aerogel target. Leading edge is surrounded by compressed aerogel (1); trailing edge (2) is mostly melted aerogel. Bottom fragment was moved from its original position during sample preparation. (c) Lunar grain that shows limited amount of attached aerogel melt. Some projectile melt may be included, although this sample was not analyzed. (d) Ca–pyroxene in a (rotated 90° from the position in a) after acid etching. Pitted area shows high-density solar flare tracks. Scale bar = 0.02 mm.
FIG. 6. (a) SEM image of a launched olivine recovered from the 5.6 km sec$^{-1}$ shot. Arrows point to olivine glass mixed with fragmented olivine on the surface. Scale bar = 15 μm. (b) SEM-BSE image of a portion of the above particle after sectioning. Rim consists of fragmented and partially melted olivine. Scale bar = 5 μm.
where \( \rho \) is the density of the projectile, \( v \) is the impact velocity, and \( a \) is the diameter of the chondrule. Thus, even a relatively large (\( a = 1 \text{ cm} \)) chondrule colliding with a very fluffy regolith (\( \rho/\rho_t = 10^{-2} \)) at 1 km sec\(^{-1} \) is stopped in a few milliseconds. The kinetic energy of the collision is thus converted to heat on a much shorter time scale than any plausible cooling mechanism can be effective. We can therefore view the situation as an instantaneous heat pulse of magnitude

\[
H = \frac{m_i v^2}{2}
\]

where \( e \) represents the efficiency of heat incorporation into the rim, \( H_f \) is the heat of fusion, \( C \) is the average specific heat, and \( \Delta T \) is the temperature difference between the melting point and the preimpact temperature of the chondrule. The value of \( H_f + C \Delta T \approx 3 \times 10^{10} \text{ erg g}^{-1} \); thus, if \( e = \frac{1}{2} \), the formation of a typical rim of width 0.1a requires an impact velocity of 2 km sec\(^{-1} \).

Whether or not these velocities are realistic for chondrule/parent body encounters is problematic. The average encounter velocities of bodies at the distance of the asteroid belt would be 2 km sec\(^{-1} \) if their average eccentricity and inclination were 0.1 and 4°, respectively (e.g., Greenzweig and Lissauer 1990). Typical collisional velocities in the asteroid belt are presently 5 km sec\(^{-1} \) (Davis et al. 1979), but were certainly lower in the past. Weidenschilling (1977) has shown that the presence of nebular gas would induce relative velocities between bodies of different sizes, but these are generally less than 0.1 km/sec. To attain relative velocities in the kilometer/second range by local gravitational scattering, the presence of lunar-sized bodies is required. However, unlike
the objects postulated by Podolak et al. (1990) to explain the secondary processing of CAIs, the chondrite target bodies must be small enough to be essentially devoid of atmosphere if chondrules are to avoid significant deceleration before striking the regolith.

Another issue is that of chondrule survivability. Clearly, low-density regoliths are required for intact capture of high-velocity chondrules. Recent studies of projectile survival at hypervelocities (Schultz and Gault 1990a,b) reveal that impact angle and target volatility are also important. With regard to the latter factor, Schultz (1988) recovered intact an AI sphere (diameter = 0.635 cm) fired into a solid block of pure water ice at 5 km sec\(^{-1}\), but a comparable impact into a nominal regolith (density = 1.5 g cm\(^{-3}\)) resulted in complete impactor disruption. The preliminary experiments described here were designed for intact capture of fired projectiles so that their characteristics could be ascertained and compared with rimmed chondrules. What target material would provide an appropriate analog for the regolith of a UOC parent body? UOCs typically contain between 10 and 15 vol% matrix (e.g., Huss et al. 1981, Grossman et al. 1988), although some chondrites contain rimmed chondrules and very little fine-grained matrix, e.g., Semarkona. Alexander et al. (1989a) conclude that rims and matrix in two UOC samples, Semarkona and Bishunpur, have experienced in situ hydrous alteration, which suggests the possibility that the regolith contained a mixture of chondrules and frozen volatiles. Future experiments will attempt to simulate impacts into fine particulate and volatile-rich materials.

VI. SUMMARY AND CONCLUSIONS

Clearly, chondrules have undergone episodal modifications since their formation. Some of these changes may have occurred within the environment of a parent body. Petrographic and SEM observations of Weston rims indicate that they may have formed via short-lived, high-energy events that thermally and/or mechanically altered the outer portions of most constituent chondrules. We suggest that chondrule granular rims as defined from observations in this paper have been produced by impact of chondrules with a parent body. Chondrule granular rims are composed of mostly host components and a low number of matrix grains, which is inconsistent with randomly acquired dust grains by accretion in the nebula. Nor have the rims formed exclusively from meteorite matrix, for the same reason. Fe-rich (opaque) rims may have been produced by melting or partial melting and fragmentation of the outer margin of the host chondrule during impact penetration.

This impact origin for chondrule rims is testable by experimentation. Light gas gun (LGG) experiments have been used to simulate accreting particle/parent body interactions. Experiments show that projectiles partially melt and fragment to degrees dependent upon the projectile velocity and form intact rims that may encompass the projectile (chondrites may contain rims produced over a wide range of impact velocities). Our rim formation hypothesis is consistent with these data in that the intact experimental rims are composed of fused and fragmental materials from both the target medium and the projectile (Weston granular and opaque rims contain fragments of both the host chondrules and matrix).

We have demonstrated that experimental hypervelocity projectiles form rims of fragmented projectile and partially melted material upon collision with a low-density target. Future experiments can better approximate accreting parent body conditions by using dusty, volatile-rich targets with millimeter-sized impactors. It is an exciting prospect that processes which occurred in the early stage of the solar system can be tested in such a direct manner.

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