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1 Are hypervelocity impacts able to produce chondrule-like ejecta?

2

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15

16 **Abstract**

17 Chondrules are one of the major components of primitive meteorites. Their sphericity
18 indicates they formed as molten fragments or droplets but conditions and mechanisms of
19 chondrule formation remain unknown. A possible scenario is their formation during
20 hypervelocity impacts and ejections. To challenge this idea, we prepared an experiment that
21 reproduces analogous of iron metal -rich chondrules by impact between a glassy silicate
22 projectile and a metallic steel target. The hypervelocity experiment setting allowed an impact
23 velocity of 5 km/s, and was also designed to collect the ejecta. A scanning electron
24 microscopy survey shows that silicate ejecta share several similarities with chondrules. They
25 formed from a population of small melt fragments whose size distribution has the same shape
26 as the size distribution of chondrules, with a shift in size: ejecta are about one order of

27 magnitude smaller than typical chondrules ($\log(d_{chondrules}/d_{ejecta}) = 1.3_{-0.7}^{+0.5}$). We attribute this
28 difference in size to the large discrepancy in the size of the impactors (only small 3 mm
29 particle in our experiment versus km-scale planetesimal expected in an impact forming
30 scenario for chondrules). The silicate ejecta formed in the ejecta plume contains numerous
31 small size spherical iron metal beads. Such beads are also observed in numerous chondrules
32 of CO chondrites specifically presented here but also documented in L and LL ordinary
33 chondrites. Size distributions of metal beads in ejecta and chondrules of a carbonaceous
34 chondrite used as reference material (Yamato 81020 CO) display a same shape but with a size
35 shift, quite similar to the one observed between the ejecta droplets and the chondrules: the
36 diameter of metal beads in ejecta is about one order of magnitude smaller than the diameter of
37 the ejecta themselves ($\log(d_{ejecta}/d_{metal\ beads\ in\ ejecta}) = 1.2_{-0.8}^{+0.9}$), and the diameter of metal beads
38 in chondrules is about one order of magnitude smaller than the diameter of the chondrules
39 themselves ($\log(d_{chondrules}/d_{metal\ beads\ in\ chondrules}) = 1.4_{-1.0}^{+0.6}$). We attribute this size differences to
40 the blast dynamics: for a same velocity and surface tension, fragments of silicate liquid will
41 be stable when iron liquid fragments of similar size will be separated into smaller droplets. In
42 our experiment, the biggest iron metal beads ($\sim 7\ \mu\text{m}$) are within the mean size range of
43 silicate ejecta and can be considered as analogous of the rare large rounded metallic grains
44 (nearly the same size as chondrules) documented in CB chondrites. The textural analogies
45 exposed here provide support for a production of chondrules by impact.

46

47 **1. Introduction**

48 Chondrites, the most primitive meteorites, are considered as the main building block of
49 early planetesimals (e.g. Scott, 2007) and are composed in various proportion – up to 80 vol%
50 for ordinary chondrites (Jones et al., 2002) – of chondrules. Chondrules are spherules largely
51 consisting of the silicate minerals olivine and pyroxene formed at high temperatures as

52 dispersed molten droplets that likely contain much important information on the processes of
53 the planetary formation.

54 Chondrules size distribution is generally quite homogeneous (0.1 to 2 mm in diameter;
55 e.g. Teitler et al., 2010). The size distribution of chondrules is typically determined by
56 disaggregation (e.g. Cuzzi et al., 2001), a method that may undercount very small and/or
57 relatively friable chondrule types, and by thin section measurements (e.g. Eisenhour, 1996), a
58 method that requires corrections of the measured size distribution to estimate “true” three-
59 dimensional grain sizes from random two-dimensional sections. These technics are not
60 accurate in counting very small “microchondrules” (5-40 μm in diameter), found in the matrix
61 or in rare clasts in at least a few chondrites, and “megachondrules” (>1 cm in diameter),
62 discovered as fragments (Nagahara, 1984; Rubin et al., 1982; Ruzicka et al., 1998).

63 Chondrule sizes and masses in various samples have been described as following lognormal
64 (King and King, 1979), Rosin or Weibull distributions (Eisenhour, 1996; Hughes, 1978a,
65 1978b) even if Teitler et al. (Teitler et al., 2010) explained that for some chondrule data sets,
66 lognormal or Weibull functions are statistically not good fits of the size distribution.
67 Nevertheless, the size distribution displays a non-zero minimum chondrule size, typically
68 about 10-20% of the mean size (Eisenhour, 1996). Each chemical group of chondrite
69 possesses a distinct size-frequency distribution of chondrules. The mean size is quite uniform
70 with ordinary chondrites (L, LL) having the largest, carbonaceous chondrite from Mighei and
71 Ornans groups (CM and CO) having lower average size (King and King, 1978) and
72 carbonaceous chondrite with high metal content (CH) displaying even lower size (e.g.
73 Grossman et al., 1988; Scott, 1988).

74 The process responsible for the formation of chondrules is still a matter of debate and
75 it is even not established if a unique or multiple distinct processes are required to form
76 chondrules. The igneous textures of chondrules indicate that they were produced by melting

77 and solidification in the early solar nebula (e.g. Scott, 2007). There are several hypothesis
78 proposed, including the formation of chondrules by planetesimal collisions (Johnson et al.,
79 2018, 2015; Johnson and Melosh, 2014; Urey, 1952), by splashing molten planetesimals
80 where energy for melting is radioactivity (e.g. Asphaug et al., 2011; Sanders and Scott, 2018),
81 by shock waves (Connolly and Love, 1998; Morris and Boley, 2018) or other processes
82 including for instance X-wind model (Shu et al., 1996), lightning (Pilipp et al., 1998), radiant
83 heating by magma ocean (Herbst and Greenwood, 2016), or localized magnetized dissipation
84 (Joung et al., 2004).

85 Krot et al. (2014, 2005) demonstrated that at least some of the latest (~5 Ma post-
86 Calcium-Aluminium-rich Inclusions (CAI), the oldest substances in the Solar System) iron-
87 rich chondrules from Carbonaceous Bencubbin-type (CB) and Carbonaceous “High-metal”
88 chondrites (CH) formed by impact. An impact origin is clearly established, in this particular
89 case, and the chondrules and metal grains in the CB chondrites would have formed from a
90 vapor–melt plume produced by a catastrophic disruption between planetary embryos. The
91 remaining question is whether most chondrules are derived from disrupted planetesimals or if
92 CB and CH are exceptions. In other chondrite groups, as in L, LL or CO, chondrules
93 frequently contain iron-nickel metal spherules, distributed in their interiors and/or located at
94 their surface. Where the metal is located at the surface of the chondrules, the shape is not
95 spherical (e.g. Uesugi et al., 2008) and the metal forms an asymmetric globule. In most other
96 cases where the metal beads are inside the chondrules, the shape is spherical. Such spherical
97 shape of both chondrules and metal beads is an evidence for a liquid behavior before their
98 solidification (Rambaldi and Wasson, 1981; Skinner and Leenhouts, 1993; Wang et al., 2007)
99 that requires the presence of two distinct and immiscible molten phases.

100 Our objective here was to perform a hypervelocity impact experiment to investigate
101 the textural properties of ejected material and to compare to the textural properties of iron

102 metal beads bearing chondrules. Here we aimed at performing impact at a velocity close to
103 that expected in the main asteroid belt (Bottke Jr et al., 1994) and a possible order of
104 magnitude of impact velocity in the protoplanetary disk (~ 5.3 km/s). Is it possible to
105 reproduce chondrule-like objects by shooting a silicate projectile into an iron metal target? Is
106 the mechanical process that create a contrasted distribution of metal and silicate liquid
107 droplets in chondrule acting in the hypervelocity impact experiment? This study will help to
108 discuss some physical properties of the spray produced during an impact and the possibility
109 that such chondrules formed from impact during the early Solar System history.

110

111 **2. Experimental setup**

112 **2.1. The impact experiment**

113 Impact experiment was conducted using a two-stage light-gas gun at Institute of Space and
114 Astronautical Science (ISAS), Japan, where projectile can be accelerated at the impact
115 velocity up to ~7 km/s, which is comparable to typical asteroid-belt collisional velocity
116 (5.3 km/s; Bottke et al., 1994). The projectile was a dunite cylinder, 0.074 g in mass, 3.2 mm
117 in diameter and 3 mm in thickness. The measured impact velocity (4.909 km/s) was close to
118 the one we planned (5 km/s). The target was a steel cylinder used in a previous study (Ganino
119 et al., 2018). The chamber was evacuated to 3 Pa. The trajectory of the projectile and ejecta
120 was captured by a high-speed video camera (Shimazu HPV-X). The camera was operated
121 with frame interval of 2 μ s with 0.5 μ s exposure and the spatial resolution is about 0.3
122 mm/pixel. The ejecta plume contains thousands of ejecta that were collected on aluminum
123 witness plates used as “ejecta catchers” (Figure 1). As this unique shoot provides thousands of
124 ejecta to characterize we limited our statistical analysis to one experiment.

125

126 **2.2. Imaging and analyzing major elements using SEM(-EDX)**

127 The analyses of the ejecta was performed using the Scanning Electron Microscope
128 Philipps FEI XL30 ESEM LaB6 equipped with a BRUKER Quantax 655 detector, operated at
129 20 kV and 200 nA beam current at CEMEF-Mines ParisTech.

130 **2.3. Particle size distribution determination**

131 The contrasted composition of the iron-rich ejecta, the aluminum plates used as ejecta
132 catcher and the SiO₂ –rich ejecta measured using Energy-dispersive X-ray spectroscopy
133 (Ganino et al., 2018) resulted in contrasted gray level on the backscattered electron image
134 (Figure 2), allowing a convenient detection and identification. We used the particle analyser
135 tool of ImageJ software to count and measure the size distribution of both the SiO₂ ejecta and
136 the metal beads contained within the ejecta.

137 In this article we call melt “fragments” or melt “droplets” the molten material, droplets
138 being the result of break-up of fragments following Johnson and Melosh (Johnson and
139 Melosh, 2014), and “beads” the spherical solidified material (e.g., metal spherules in
140 chondrules or in ejecta). As we wanted to estimate the size of the melt fragments and droplets
141 produced during the impact rather than that of the flattened “splashed” ejecta on the
142 aluminum plate, we measured the surface and estimated the volume of observed splashed
143 ejecta and recalculated the diameter of an equivalent sphere. Assumption for this calculation
144 is that most splashed ejecta were 1 µm- thick as inferred from tilted SEM image of the ejecta
145 catcher. 9326 ejecta were measured. Thirteen ejecta were randomly chosen and focused on for
146 determination of the size distribution of the 1625 metal beads they contained. These thirteen
147 ejecta display a large scale range (Figure 2).

148 **2.4. Distribution of metal beads in chondrules**

149 The presence of metal beads in chondrules is well known, but their size distribution is not
150 documented and their abundance largely differs from a chondrite family to another (Scott and
151 Krot, 2003). We used back-scattered electron image of the carbonaceous chondrite

152 Yamato 81020 (CO 3.0) (Figure 3) to describe the size distribution of metal beads. Yamato
153 81020 is a perfect sample for this study because it is a primitive object (carbonaceous
154 chondrite, see Libourel et al, 2017) poorly altered (no sulfidation, etc), and it is a metal rich-
155 chondrite with abundant metal beads in the large majority of its chondrules. In the same way
156 to the procedure that we used to determine the size distribution of the ejecta in the
157 experiment, we used the particle analyser tool of ImageJ software to count and measure the
158 2D-size distribution of metal beads contained within the chondrules of Yamato 81020. Here,
159 the data are apparent diameters measured on a two-dimensional surface and include sections
160 of metal beads. When the sample is sectioned, not all particles/grains are sectioned through
161 their maximum diameter, many appear smaller than they actually are. The size distribution is
162 therefore, inherently biased to smaller sizes. The measured size distribution can be corrected
163 with a stereological analysis. We used, a classical Saltykov analysis (Saltykov, 1958) also
164 called “Schwartz-Saltykov”, that allows to compute a statistical equivalent 3D size
165 distribution from a 2D size distribution considering that the grains are represented by their
166 equivalent spheres.

167

168 **3. Results**

169 **3.1. Chondrule size distribution in CO chondrites**

170 CO chondrites have different types of chondrules, some of which are non-spherical
171 and present a wide range of shapes (Figure 3). Rubin and Wasson (2005) show that some
172 chondrules in Yamato 81020 are multi-lobate or distended or highly irregular in two
173 dimensions. The circular chondrules are moderately equant with aspect ratios in thin section
174 varying from 1.02 to 1.11.

175 The size-frequency distribution of 2834 chondrules in CO chondrites was determined
176 by petrographic analysis of thin sections by Rubin (1989). The data are not corrected and

177 apparent diameters were measured on a two-dimensional surface and display a mean of
178 148_{-70}^{+132} μm . We used the initial two dimensional chondrule size distribution of Rubin
179 (Rubin, 1989) transformed into a theoretical three dimensional size distribution after a
180 Saltykov analysis (Saltykov, 1958).

181 The chondrule theoretical three-dimensional size distribution best fit is a Rosin
182 distribution (Hughes, 1978a) expressed as

$$ch\% = 100 * (1 - e^{-bd^n}) \quad (1)$$

183 where $ch\%$ is the percentage of chondrules, d is the diameter in micron and b and n are
184 constants and are parameters of the distribution (respectively $1/b$ being the scale parameter
185 and n being the shape parameter). For our best fit, $b = -2.60$ and $n = 1.13$. The correlation
186 coefficient of the linear regression in the plot $\log(-\ln(1-ch\%)) = f(\log(d))$ is very good ($r = -$
187 0.96). Following the results from Hughes (Hughes, 1978a) a better correlation ($r = 0.99$) is
188 obtained using a 3 parameters Weibull law distribution expressed as

$$ch\% = 100 * (1 - e^{-b(d-\gamma)^n}) \quad (2)$$

189 where γ is the location parameter and with best fit for $\gamma = 131 \mu m$, $b = -1.35$ and $n = 0.74$.

190 The excellent correlation coefficients demonstrate we are in the case where Rosin and three
191 parameters Weibull laws fit the dataset as very often for chondrules (Hughes, 1978a; Teitler
192 et al., 2010).

193

194 **3.2. Silicate ejecta size distribution in high velocity impact plume**

195 Ejecta we collected appear as stuck patches on the ejecta catcher with a nearly circular
196 shape, a typical thickness of $1 \mu m$ and an apparent diameter that largely varies from $3.7 \mu m$ to
197 $61.2 \mu m$. As all ejecta present a circular shape, we infer they were all formed from splashing
198 melt fragments and droplets.

199 Despite the relatively low impact energy due to the small size of the projectile, our
200 impact experiment provides abundant melted material. In fact, a precise quantification is not
201 straightforward, but at a first glance, most ejecta have rounded shapes and result from
202 solidification of molten material whereas only rare, always metallic, fragments are angular
203 and could be remnants of unmolten pieces of the target. Because of the exposure duration of
204 the high velocity camera (0.5 μ s), the ejecta particles with a velocity of 5 km/s moved of \sim 2.5
205 mm during the exposure. In other words, the ejecta particles appear by 2.5 mm longer than
206 they are. Moreover, the spatial resolution of the camera was not sufficient (>0.3 mm/pixel)
207 to determine the size distribution of ejected material during the flight. Therefore, what we can
208 observe on the images (Figure 1) are only slow ($<$ km/s) and relatively large ($>$ mm)
209 fragments. To characterize the ejecta population, we use the ejecta catcher. Our experimental
210 setting was not appropriate to sample the whole plume of ejecta, but we find only rare angular
211 fragments, generally of iron-metal (from the target) and relatively large ($>100\mu$ m) that were
212 ejected during the impact. The remaining ejecta collected on the aluminum plate have a
213 rounded shape compatible with a pronounced melting of silicate (from the projectile) and
214 metal (from the target) material.

215 The size of the silicate ejecta recovered on the ejecta catcher and that come from the
216 major mass of the ejecta plume is related to fragments and droplets with a diameter in the
217 range \sim 4-17 μ m (mean = 7.87 μ m, median = $6.43^{+10.31}_{-2.49}$ μ m; the confidence interval
218 calculated to include 90% of the sample data within). The size distribution of the ejecta is
219 very similar in shape with the size distribution of chondrules (Figure 4) and fits a Rosin
220 distribution as in equation (1). In our best fit for the size distribution of silicate ejecta, $b = -$
221 0.88 and $n = 1.04$. The correlation coefficient of the linear regression in the plot $\log(-\ln(1-$
222 $ej\%) = f(\log(d))$ where $ej\%$ is the percentage of ejecta and d the diameter is very good

223 ($r = 0.97$). Here again, a better correlation ($r = 0.99$) is obtained using a three-parameters
224 Weibull law with $\gamma = 5.3 \mu m$, $b = -0.17$ and $n = 0.62$.

225

226 **3.3. Metal beads size distribution in ejecta and chondrules of Yamato 81020 (CO 3.0)**

227 The silicate ejecta formed in the ejecta plume contains numerous small size (mostly
228 $<1 \mu m$) spherical iron metal beads (Figure 2). Metal beads were observed and measured in 13
229 randomly chosen ejecta. All beads are in the range 0.07 - $7.0 \mu m$ with a mean size of $0.55 \mu m$
230 and a median of $0.40_{-0.26}^{+0.99} \mu m$. The size distribution was plotted for the independently
231 analyzed ejecta (thin dotted-lines in Figure 4d) and for the sum of all beads (1625 beads) in
232 that 13 ejecta (thick dotted-line in Figure 4d). The distribution follows a Rosin size
233 distribution ($r = 0.98$) with $b = 0.36$ and $n = 0.55$ or a three-parameter Weibull distribution
234 ($r = 0.99$) with $\gamma = 0.53 \mu m$, $b = 0.50$ and $n = 0.36$.

235 Even if they are generally much larger (up to few tens of micrometers), such spherical
236 metal beads are very frequent in chondrules of the carbonaceous chondrite Yamato 81020
237 (CO 3.0). In that meteorite, many chondrules contain metal bead. We observed and measured
238 the size of metal beads in nine randomly chosen chondrules from Yamato 81020. From the
239 two-dimensional size distribution, we calculated the theoretical three-dimensional size
240 distribution after a Saltykov analysis (Saltykov, 1958). Their diameter range is $2.1 - 81.1 \mu m$
241 with a mean of $9.38 \mu m$ and a median of $5.65_{-3.21}^{+23.00} \mu m$. Here again, the size distribution was
242 plotted for the independently analyzed chondrules (thin dotted-lines in Figure 4c) and for the
243 sum of all beads (3517 beads) in that 9 chondrules (thick dotted-line in Figure 4c). The
244 distribution follows with an excellent fit ($r = 0.99$) a Rosin size distribution with $b = -0.77$ and
245 $n = 0.95$ or a three-parameter Weibull distribution ($r = 0.99$) with $\gamma = 4.71 \mu m$, $b = -0.44$ and
246 $n = 0.77$.

247

248 **4. Discussion**

249 **4.1. Size of chondrules, metal beads and ejecta**

250 Distinct size-frequency chondrule distributions made some authors propose a sorting
251 mechanism, as for instance aerodynamic drag (Dodd, 1976; Shu et al., 1996). Following the
252 idea of an impact origin for chondrules, their mean size would then be explained by the
253 solidification of ejected melt fragments and droplets produced by impactors <10 km in
254 diameter (Benoit et al., 1999; Melosh and Vickery, 1991).

255 The textural homogeneity observed in our ejecta and chondrules, with silicate and
256 metal droplets having similar pattern of size distribution, suggests that material experienced
257 mechanical sorting. The particles might have been size-sorted under virtually identical
258 conditions and following a similar physical process. The material initially shocked to high
259 pressure could have approached the liquid-vapor phase boundary from the liquid side during
260 decompression: the formation of a condensate layer formed from a gas phase during the
261 experiment was documented by Ganino et al. (Ganino et al., 2018). The decompression
262 caused the break-up into an expanding spray of melt fragments and droplets of the ejecta
263 blast. Following Melosh and Vickery (Melosh and Vickery, 1991), the equilibrium droplet
264 radius (R) depends on the size of the impactor (L) and the impact velocity (v_{imp}) following the
265 equation

266

267
$$R = 0.11 \frac{\sqrt{L}}{v_{imp}} (3)$$

268

269 With this model, mean size of chondrules would then be explained by the solidification of
270 ejected melt fragments produced by impactors <10 km in diameter (Benoit et al., 1999).

271 When we apply this equation to the ejecta produced during the hypervelocity experiment, we
272 find that expected radius for a 3 mm impactor shot at 4.909 km/s is about 1.2 μm , equivalent

273 to a diameter of $\sim 2.4 \mu\text{m}$. This estimate is too small compared to what we observed. Melosh
274 and Vickery (Melosh and Vickery, 1991) modeling corresponds to melt ejection as a half
275 sphere expanding into free space, a geometry that closely represents the geometry of a vapor
276 plume, while the ejecta plume in our experiment presents a significantly different geometry
277 (Figure 1). Johnson and Melosh (Johnson and Melosh, 2014) performed impact simulations
278 using the hydrocode modelling iSALE to constrain the properties of the ejecta curtain. To
279 calculate the size (diameter) of ejected melt fragments as a function of ejection velocity,
280 impact velocity, and impactor size they proposed the following equation (Johnson and
281 Melosh, 2014),

$$282 \quad d_{\text{fragments}} \sim 0.14 \left(\frac{v_{ej}}{v_{imp}} \right)^{-0.81} \left(\frac{R_{imp}}{v_{imp}} \right)^{\frac{2}{3}} \quad (4)$$

283
284 When analyzing the high-speed video images, the leading edge of the ejecta cloud had
285 velocity of $\sim 4.6 \text{ km/s}$ corresponding to an estimate of the ejection velocity used in equation
286 (4). With this value, the theoretical size of melt fragments calculated from Johnson and
287 Melosh (Johnson and Melosh, 2014) equation would be $d_{\text{fragments}} = 6.69 \mu\text{m}$. The expected
288 diameter for melt fragment is close to the mean diameter of the ejecta we observed
289 (mean = $7.87 \mu\text{m}$, median = $6.43_{-2.49}^{+10.31} \mu\text{m}$) making us propose that the physical process
290 described in this equation could explain the observations from our experiment. In the post-
291 impact blast, when fragmentation occurs in the ejecta plume, ejected melt fragments can be
292 accelerated by aerodynamic drag as the surrounding vapor flows past the melt. The balance of
293 the aerodynamic drag force and surface tension determines the size of the melt droplets. In
294 that case, the size of the ejecta we collected and measured on the ejecta-catcher depends on
295 the size of the melt fragments in the impact plume that might be governed by the balance
296 between the surface tension and relative kinetic energy. Johnson and Melosh (Johnson and
297 Melosh, 2014), argued that melt “droplets” also form during the blast, as a result of break-up

298 of larger melt fragments and proposed an equation to estimate the size (diameter) of melt
299 droplets:

$$300 \quad d_{droplets} \sim 0.025 \left(\frac{v_{ej}}{v_{imp}} \right)^{-0.97} R_{imp}^{\frac{1}{2}} v_{imp}^{-1} \quad (5)$$

301 For our experiment, the theoretical diameter of melt droplets calculated from Johnson and
302 Melosh (Johnson and Melosh, 2014) equation would be $d_{droplets} = 0.21 \mu\text{m}$. This size is clearly
303 too low to explain the observed size distribution of silicate ejecta. Nevertheless, it is close to
304 the order of magnitude of the diameter of the metal beads found in the ejecta (mean = 0.55;
305 median = $0.40_{-0.26}^{+0.99} \mu\text{m}$) that could be explained, following Johnson and Melosh (Johnson and
306 Melosh, 2014) process, by the break-up of larger melt fragments of metal.

307 In our quantitative study, the difference between the size of chondrules in CO, the size
308 of ejecta in hypervelocity experiment and the sizes of metal beads in chondrules and in ejecta
309 can be obtained quantifying the horizontal shift between the distribution curves (Figure 5): the
310 diameter of metal beads in ejecta is ~ 1.2 order of magnitude smaller than the diameter of the
311 ejecta themselves ($\log(d_{ejecta}/d_{metal\ beads\ in\ ejecta}) = 1.2_{-0.8}^{+0.9}$), and the diameter of metal beads in
312 chondrules is ~ 1.4 magnitude smaller than the diameter of the chondrules themselves
313 ($\log(d_{chondrules}/d_{metal\ beads\ in\ chondrules}) = 1.4_{-1.0}^{+0.6}$). These results can also be deduced from the 3
314 parameters Weibull law distributions we obtained for our data. The shape parameter (n) is
315 very close for all distribution ($n_{chondrules} = 0.74$; $n_{ejecta} = 0.62$; $n_{beads\ in\ chondrules} = 0.77$; $n_{beads\ in}$
316 $ejecta} = 0.36$), and if we focused on the location parameter (γ), we confirm that there is a one
317 order of magnitude shift between the diameter of chondrules and the diameter of metal beads
318 in chondrules ($\log(\gamma_{chondrules}/\gamma_{metal\ beads\ in\ chondrules}) = 1.4$) and between the diameter of
319 ejecta and the diameter of metal beads in ejecta ($\log(\gamma_{ejecta}/\gamma_{metal\ beads\ in\ ejecta}) = 1$).

320 That discrepancy would suggest that the physical process that created a contrasted distribution
321 of metal beads and silicated chondrules in chondrites might govern similar distributions in the
322 hypervelocity impact experiment. The process proposed by Johnson and Melosh (Johnson and
323 Melosh, 2014) could explain the contrasted size between silicate ejecta and metal beads :it
324 would be related to the break-up of melt fragments into smaller melt droplets that would
325 occur for metal melt but not for silicate melt. A way to analyze the flow regime in a
326 multiphase fluid flows is to calculate the Weber number (We). This dimensionless parameter
327 is defined as the ratio of the momentum in the vapor layer divided by the surface tension force
328 restraining the liquid following the equation

329

$$330 \quad We = \frac{\rho v_f^2 l}{\sigma} \quad (6)$$

331

332 where ρ is the density of the fluid, v_f is its velocity, l is its characteristic length, for instance
333 the droplet diameter and σ is the surface tension. There is a critical Weber number (We_c)
334 above which drop break-up occurs. This critical number depends on the fluid properties but is
335 generally close to 12 (e.g. Pilch and Erdman, 1987). In our experiment during the post-impact
336 blast illustrated by Figure 1, the ejecta were propelled as high velocity relatively thick
337 filaments (Figure 1 and Ganino et al., 2018). The intricate non-spherical shapes of the
338 filaments show that the Weber number (We) for the fluid flow is high and should drive a first
339 break-up into small spherical fragments by sheet stripping (Chigier and Reitz, 1996). Density
340 being higher in iron liquid than in silicate liquid, for a same velocity and surface tension,
341 fragments of silicate liquid will be stable ($We_{\text{silicate melt fragments}} < We_{\text{critical}}$) when iron liquid
342 fragments of similar size will be separated by a second break-up from “melt fragments” to
343 “melt droplets” ($We_{\text{iron melt fragments}} > We_{\text{critical}}$). If this scenario of droplets formation by sheet
344 stripping is true, the size sorting between the silicate droplet and the smaller metal droplet

345 would be acting and efficient in an extremely short scale (the flight length is about 10 cm) and
346 timescale (the flight duration is few tens of μs).

347 These results could explain the mean size of metal beads versus silicate ejecta or
348 chondrules. If we now look at the extreme values, i.e. the biggest metal beads produced
349 during the experiment (size = $7.0 \mu\text{m}$), it is of note that they are very close to the mean and
350 median size of silicate ejecta (mean = $7.87 \mu\text{m}$, median = $6.43_{-2.49}^{+10.31} \mu\text{m}$). The largest metal
351 beads in our experiment would be derived from melt fragments of metal that did not break-up
352 into smaller melt droplets. A possible explanation would be that their We number was too low
353 ($We_{\text{iron melt fragments}} < We_{\text{critical}}$), and it could be the case if these melt fragments were ejected
354 with a velocity below the average, or if their temperature was slightly different, resulting in
355 distinct surface tension, We number, and mechanical behavior during the blast. In a planetary
356 perspective, large metal beads with a diameter close to the typical diameter of chondrules are
357 also documented and are also relatively rare. Large metal beads are described in some
358 chondrites where their size range is similar to the size of chondrules, as for instance the
359 “large” metallic grains found in CB (Krot et al., 2005).

360

361 **4.2. Origin of the metal beads in chondrules**

362 In natural samples, as in Yamato 81020, not all chondrules display abundant iron-
363 metal beads (see also Libourel and Portail, 2018). An explanation could be that all chondrules
364 initially contained iron droplets, but separation operated to various degrees between melted
365 iron globules and melted chondrules (Uesugi et al., 2008). Size sorting of metal and silicate
366 fractions might suggest that sorting of metallic beads is linked to a certain extent to the
367 siderophile depletion in chondrites (following Skinner and Leenhouts, 1993).

368 Another explanation would be that the iron-bead content is directly related to the
369 elementary abundance of iron that may strongly differ from one chondrule to another. In the

370 case chondrules were formed by impact, the chemical composition of the planetary bodies
371 involved in the impact are of first importance: impact involving iron-rich differentiated bodies
372 would involve larger volume of metal-rich ejecta. With our experimental setting, it is clear
373 that a significant proportion of metal beads may be molten fragments of the steel target
374 (Ganino et al., 2018). The processes of projectile–target interaction and inter-element
375 fractionation during and immediately after the impact process are now well documented (e.g.
376 Ebert et al., 2013; Evans et al., 1994; Hamann et al., 2013; Mittlefehldt et al., 2005, 1992).
377 Nevertheless, another process could be involved in the occurrence of iron-metal, as the high
378 temperature reached during the impact may cause the reduction of FeO contained in the
379 silicate projectiles into iron metal following the reaction:



381 Shock induced in-situ reduction of FeO is well known during hypervelocity and
382 impact experiments (Ganino et al., 2018; Rowan and Ahrens, 1994) and examples are
383 described in natural craters on Earth where iron metal spheres are also observed disseminated
384 in silicate impact melt (e.g., Meteor Crater and Wabar craters, respectively, described by
385 Mittlefehldt et al., 2005 and Hamann et al., 2013).

386 Hypervelocity impact experiment carried out in this study provides further support to
387 an impact forming scenario for chondrule formation: similarly, in catastrophic disruption
388 between large bodies, immiscibility may occur between the silicate and iron liquids – the
389 latter forming from iron metal initially present in the colliding bodies or forming from FeO
390 reduction when the temperature rises.

391 In this article, we underlined the remarkable analogies between chondrules size
392 distribution in CO carbonaceous chondrites and ejecta formed in the hypervelocity
393 experiment. We also mentioned the striking analogies in their metal-beads contents, following
394 the idea that a similar sorting mechanism could act. Important aspects remain to be discussed

395 as the other proxies we can use to challenge such scenario and the possible chronology in the
396 early history of the Solar System. The thermal history of chondrules brings constraints that
397 could help to discriminate between chondrule formation models (Jones et al., 2018).
398 Porphyritic textures are produced when a chondrule is heated to a maximum temperature
399 close to its liquidus (typically 1400 to 1700°C), and cooled at initial rates between about 10
400 and 1,000 °C/h. Nonporphyritic chondrules develop when peak temperatures exceed the
401 liquidus and chondrules cool at rates around 500–3,000 °C/h. In our experiment, ejecta
402 remain glassy; such conditions being closed to those of hyper-quench (cooling rate of several
403 10^5 - 10^6 °C.s⁻¹). What would be expected in larger ejecta blast? A modelling of the radiative
404 cooling of a ballistically expanding spherical cloud of chondrule droplets ejected from the
405 impact site is proposed by Dullemond et al. (2014). This article confirm its compatibility with
406 the cooling history of chondrules inferred from the texture, and mineral composition (Jones et
407 al., 2018). Radiative cooling of a droplet cloud produces cooling rates that can be related not
408 only to the different types of texture of the chondrules but also to their relative abundance
409 (Delpeyrat et al., 2019). Focusing on jetted material, Johnson et al. (Johnson et al., 2015)
410 demonstrated that melted droplets jetted during large-scale accretionary impacts would also
411 exhibit the observed igneous textures of chondrules. In a chondrule forming process
412 associated to impact involving molten planetesimals (Asphaug et al., 2011) the cooling rate,
413 limited by opacity, is regulated by the expansion timescale and depends on local swarm
414 density and proximity to the boundary. In this case, chondrules can be used as proxy to
415 constrain the swarm dynamics.

416 Nevertheless, the formation of chondrules from large impact questions the early
417 evolution of the Solar System: chondrule formation would occur when planetesimals and their
418 collisions were abundant and it is generally believed that planetesimals would only accrete
419 once chondrules formed. A support to this scenario, that seems contradictory at a first glance,

420 comes from isotopic analyses of magmatic iron meteorites (Kruijer et al., 2014). These
421 analyses bring support to a possible synchronicity of planetesimal and chondrules formation,
422 showing that the parent bodies of magmatic iron meteorites greater than 10–100 km in
423 diameter could have accreted ~0.1–0.3 Myr after the formation of CAIs. With a such age,
424 some planetesimals would have formed before most chondrules and chondrites would not be
425 the direct primitive accreting blocks of that planetesimals, but a consequence of their
426 accretion.

427

428 **Conclusion**

429 The hypervelocity experiment presented here, involving a silicate projectile on an iron
430 metal target, produces ejecta that share several similarities with metal beads rich chondrules.
431 These ejecta appear as largely molten splashed ejecta sampled on a screen, coming from a
432 population of small melt fragments and droplets. The size distribution of the ejecta is similar
433 to the size distribution of chondrules in CO chondrites, with a shift in size. The ejecta were
434 about an order of magnitude smaller than CO chondrules, a result that is expected by the fact
435 that the equilibrium melt fragments size depends on is the size of the impactor (small 3 mm
436 particle in our experiment versus km-scale planetesimal in an impact forming scenario for
437 chondrules). The silicate ejecta formed in the ejecta plume contains numerous small size
438 spherical iron metal beads as consistent with what is frequently observed in chondrules. The
439 biggest iron metal droplets (~7 μ m) fall in the size mean size range of silicate ejecta and could
440 be considered as analogous of large (same size as chondrules) rounded metallic grains
441 documented in CB chondrites. The size distributions of metal beads in ejecta and chondrules
442 are similar but with a size shift: iron-metal beads in the ejecta are about an order of magnitude
443 smaller than iron-metal beads in the chondrule of Yamato 81020. We attribute the difference
444 in mean size between silicate melt (chondrule or ejecta) and metal melt (beads in chondrules

445 or beads in ejecta), to the break-up from melt “fragments” to melt “droplets”. This process
446 would be efficient for metal melt but not for silicate melt because of their different density
447 (higher in iron liquid than in silicate liquid). For a same velocity and surface tension,
448 fragments of silicate liquid were stable when iron liquid fragments of similar size were
449 separated. The remarkable textural analogies between chondrules and ejecta exposed here
450 give support for a production of chondrules during impact, implying that chondrites would not
451 be the direct primitive accreting blocks of the planets, but a byproduct of their accretion.

452

453

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464

465

466 **References**

467 Asphaug, E.I., Jutzi, M., Movshovitz, N., 2011. Chondrule formation during planetesimal
468 accretion. *Earth Planet. Sci. Lett.* <https://doi.org/10.1016/j.epsl.2011.06.007>

469 Benoit, P.H., Symes, S.J.K., Sears, D.W.G., 1999. Chondrule size distributions: What does it

470 mean?, in: Lunar and Planetary Science Conference.

471 Bottke Jr, W.F., Nolan, M.C., Greenberg, R., Kolvoord, R.A., 1994. Velocity distributions
472 among colliding asteroids. *Icarus* 107, 255–268.

473 Chigier, N., Reitz, R.D., 1996. Regimes of jet breakup and breakup mechanisms- Physical
474 aspects. *Recent Adv. spray Combust. Spray At. drop Burn. phenomena.* 1, 109–135.

475 Connolly, H.C., Love, S.G., 1998. The formation of chondrules: Petrologic tests of the shock
476 wave model. *Science* (80-.). 280, 62–67.

477 Cuzzi, J.N., Hogan, R.C., Paque, J.M., Dobrovolskis, A.R., 2001. Size-selective concentration
478 of chondrules and other small particles in protoplanetary nebula turbulence. *Astrophys. J.*
479 546, 496.

480 Delpyrat, J., Pigeonneau, F., Libourel, G., 2019. Chondrule radiative cooling in a non-
481 uniform density environment. *Icarus*.

482 Dodd, R.T., 1976. Accretion of the ordinary chondrites. *Earth Planet. Sci. Lett.* 30, 281–291.

483 Dullemond, C.P., Stammler, S.M., Johansen, A., 2014. Forming chondrules in impact
484 splashes. I. radiative cooling model. *Astrophys. J.* [https://doi.org/10.1088/0004-](https://doi.org/10.1088/0004-637X/794/1/91)
485 [637X/794/1/91](https://doi.org/10.1088/0004-637X/794/1/91)

486 Ebert, M., Hecht, L., Deutsch, A., Kenkmann, T., 2013. Chemical modification of projectile
487 residues and target material in a MEMIN cratering experiment. *Meteorit. Planet. Sci.*
488 <https://doi.org/10.1109/ICCA.2014.6870956>

489 Eisenhour, D.D., 1996. Determining chondrule size distributions from thin-section
490 measurements. *Meteorit. Planet. Sci.* 31, 243–248.

491 Evans, N.J., Shahinpoor, M., Ahrens, T.J., 1994. Hypervelocity impact: Ejecta velocity,
492 angle, and composition. *Large Meteor. Impacts Planet. Evol. Spec. Pap. (Geological Soc.*
493 *Am.* <https://doi.org/10.1130/SPE293-p93>

494 Ganino, C., Libourel, G., Nakamura, A.M., Jacomet, S., Tottreau, O., Michel, P., 2018.

495 Impact-induced chemical fractionation as inferred from hypervelocity impact
496 experiments with silicate projectiles and metallic targets. *Meteorit. Planet. Sci.* 0.
497 <https://doi.org/10.1111/maps.13131>

498 Grossman, J.N., Rubin, A.E., MacPherson, G.J., 1988. ALH85085: a unique volatile-poor
499 carbonaceous chondrite with possible implications for nebular fractionation processes.
500 *Earth Planet. Sci. Lett.* 91, 33–54. [https://doi.org/https://doi.org/10.1016/0012-](https://doi.org/10.1016/0012-821X(88)90149-5)
501 [821X\(88\)90149-5](https://doi.org/10.1016/0012-821X(88)90149-5)

502 Hamann, C., Hecht, L., Ebert, M., Wirth, R., 2013. Chemical projectile-target interaction and
503 liquid immiscibility in impact glass from the Wabar craters, Saudi Arabia. *Geochim.*
504 *Cosmochim. Acta.* <https://doi.org/10.1016/j.gca.2013.07.030>

505 Herbst, W., Greenwood, J.P., 2016. A new mechanism for chondrule formation: Radiative
506 heating by hot planetesimals. *Icarus.* <https://doi.org/10.1016/j.icarus.2015.11.026>

507 Hughes, D.W., 1978a. Chondrule mass distribution and the Rosin and Weibull statistical
508 functions. *Earth Planet. Sci. Lett.* 39, 371–376.

509 Hughes, D.W., 1978b. A disaggregation and thin section analysis of the size and mass
510 distribution of the chondrules in the Bjurböle and Chainpur meteorites. *Earth Planet. Sci.*
511 *Lett.* 38, 391–400.

512 Johnson, B.C., Ciesla, F.J., Dullemond, C.P., Melosh, H.J., 2018. Formation of Chondrules by
513 Planetesimal Collisions, in: Krot, A.N., Connolly Jr., H.C., Russell, S.S. (Eds.),
514 *Chondrules: Records of Protoplanetary Disk Processes*, Cambridge Planetary Science.
515 Cambridge University Press, Cambridge, pp. 343–360. [https://doi.org/DOI:](https://doi.org/10.1017/9781108284073.013)
516 [10.1017/9781108284073.013](https://doi.org/10.1017/9781108284073.013)

517 Johnson, B.C., Melosh, H.J., 2014. Formation of melt droplets, melt fragments, and
518 accretionary impact lapilli during a hypervelocity impact. *Icarus.*
519 <https://doi.org/10.1016/j.icarus.2013.10.022>

520 Johnson, B.C., Minton, D.A., Melosh, H.J., Zuber, M.T., 2015. Impact jetting as the origin of
521 chondrules. *Nature* 517, 339.

522 Jones, A.P., Price, G.D., Price, N.J., Decarli, P.S., Clegg, R.A., 2002. Impact induced melting
523 and the development of large igneous provinces 202, 551–561.

524 Jones, R.H., Villeneuve, J., Libourel, G., 2018. Thermal Histories of Chondrules, in: Krot,
525 A.N., Connolly Jr., H.C., Russell, S.S. (Eds.), *Chondrules: Records of Protoplanetary*
526 *Disk Processes*, Cambridge Planetary Science. Cambridge University Press, Cambridge,
527 pp. 57–90. <https://doi.org/DOI: 10.1017/9781108284073.003>

528 Jung, M.K.R., Mac Low, M.-M., Ebel, D.S., 2004. Chondrule Formation and Protoplanetary
529 Disk Heating by Current Sheets in Nonideal Magnetohydrodynamic Turbulence.
530 *Astrophys. J.* <https://doi.org/10.1086/381651>

531 King, T.V. V, King, E.A., 1979. Size frequency distributions of fluid drop chondrules in
532 ordinary chondrites. *Meteoritics* 14, 91–96.

533 King, T.V. V, King, E.A., 1978. Grain size and petrography of C2 and C3 carbonaceous
534 chondrites. *Meteoritics* 13, 47–72.

535 Krot, A.N., Amelin, Y., Cassen, P., Meibom, A., 2005. Young chondrules in CB chondrites
536 from a giant impact in the early Solar System. *Nature* 436, 989.

537 Krot, A.N., Nagashima, K., Bizzarro, M., 2014. Aluminum-magnesium isotope systematics of
538 porphyritic chondrules and plagioclase fragments in CH carbonaceous chondrites, in:
539 *Lunar and Planetary Science Conference*. p. 2142.

540 Kruijer, T.S., Touboul, M., Fischer-Gödde, M., Bermingham, K.R., Walker, R.J., Kleine, T.,
541 2014. Protracted core formation and rapid accretion of protoplanets. *Science* (80-.).
542 <https://doi.org/10.1126/science.1251766>

543 Libourel, G., Michel, P., Delbo, M., Ganino, C., Recio-Blanco, A., de Laverny, P., Zolensky,
544 M.E., Krot, A.N., 2017. Search for primitive matter in the Solar System. *Icarus* 282,

545 375–379. <https://doi.org/10.1016/j.icarus.2016.09.014>

546 Libourel, G., Portail, M., 2018. Chondrules as direct thermochemical sensors of solar
547 protoplanetary disk gas. *Sci. Adv.* 4.

548 Melosh, H.J., Vickery, A.M., 1991. Melt droplet formation in energetic impact events. *Nature*
549 350, 494.

550 Mittlefehldt, D.W., Hörz, F., See, T.H., Scott, E.R.D., Mertzman, S.A., 2005. Geochemistry
551 of target rocks, impact-melt particles, and metallic spherules from Meteor Crater,
552 Arizona: Empirical evidence on the impact process, in: *Special Paper 384: Large*
553 *Meteorite Impacts III*. <https://doi.org/10.1130/0-8137-2384-1.367>

554 Mittlefehldt, D.W., See, T.H., Hörz, F., 1992. Dissemination and fractionation of projectile
555 materials in the impact melts from Wabar Crater, Saudi Arabia. *Meteoritics*.

556 Morris, M.A., Boley, A.C., 2018. Formation of Chondrules by Shock Waves, in: Krot, A.N.,
557 Connolly Jr., H.C., Russell, S.S. (Eds.), *Chondrules: Records of Protoplanetary Disk*
558 *Processes*, Cambridge Planetary Science. Cambridge University Press, Cambridge, pp.
559 375–399. [https://doi.org/DOI: 10.1017/9781108284073.015](https://doi.org/DOI:10.1017/9781108284073.015)

560 Nagahara, H., 1984. Matrices of type 3 ordinary chondrites—Primitive nebular records.
561 *Geochim. Cosmochim. Acta* 48, 2581–2595.

562 Pilch, M., Erdman, C.A., 1987. Use of breakup time data and velocity history data to predict
563 the maximum size of stable fragments for acceleration-induced breakup of a liquid drop.
564 *Int. J. Multiph. flow* 13, 741–757.

565 Pilipp, W., Hartquist, T.W., Morfill, G.E., Levy, E.H., 1998. Chondrule formation by
566 lightning in the Protosolar Nebula? *Astron. Astrophys.*

567 Rambaldi, E.R., Wasson, J.T., 1981. Metal and associated phases in Bishunpur, a highly
568 unequilibrated ordinary chondrite. *Geochim. Cosmochim. Acta* 45, 1001–1015.

569 Rowan, L.R., Ahrens, T.J., 1994. Observations of impact-induced molten metal-silicate

570 partitioning. *Earth Planet. Sci. Lett.* [https://doi.org/10.1016/0012-821X\(94\)90052-3](https://doi.org/10.1016/0012-821X(94)90052-3)

571 Rubin, A.E., 1989. Size-frequency distributions of chondrules in CO3 chondrites. *Meteoritics*
572 24, 179–189.

573 Rubin, A.E., Scott, E.R.D., Keil, K., 1982. Microchondrule-bearing clast in the Piancaldoli
574 LL3 meteorite: a new kind of type 3 chondrite and its relevance to the history of
575 chondrules. *Geochim. Cosmochim. Acta* 46, 1763–1776.

576 Rubin, A.E., Wasson, J.T., 2005. Non-spherical lobate chondrules in CO3.0 Y-81020:
577 General implications for the formation of low-FeO porphyritic chondrules in CO
578 chondrites. *Geochim. Cosmochim. Acta.* <https://doi.org/10.1016/j.gca.2004.06.019>

579 Ruzicka, A., Snyder, G.A., Taylor, L.A., 1998. Mega-chondrules and large, igneous-textured
580 clasts in Julesberg (L3) and other ordinary chondrites: vapor-fractionation, shock-
581 melting, and chondrule formation. *Geochim. Cosmochim. Acta* 62, 1419–1442.
582 [https://doi.org/https://doi.org/10.1016/S0016-7037\(98\)00029-5](https://doi.org/https://doi.org/10.1016/S0016-7037(98)00029-5)

583 Saltykov, S.A., 1958. *Stereometric metallography.* Metall. Moscow 267.

584 Sanders, I.S., Scott, E.R.D., 2018. Making Chondrules by Splashing Molten Planetesimals, in:
585 Krot, A.N., Connolly Jr., H.C., Russell, S.S. (Eds.), *Chondrules: Records of*
586 *Protoplanetary Disk Processes*, Cambridge Planetary Science. Cambridge University
587 Press, Cambridge, pp. 361–374. [https://doi.org/DOI: 10.1017/9781108284073.014](https://doi.org/DOI:10.1017/9781108284073.014)

588 Scott, E.R.D., 2007. Chondrites and the protoplanetary disk. *Annu. Rev. Earth Planet. Sci.* 35,
589 577–620.

590 Scott, E.R.D., 1988. A new kind of primitive chondrite, Allan Hills 85085. *Earth Planet. Sci.*
591 *Lett.* 91, 1–18. [https://doi.org/https://doi.org/10.1016/0012-821X\(88\)90147-1](https://doi.org/https://doi.org/10.1016/0012-821X(88)90147-1)

592 Scott, E.R.D., Krot, A.N., 2003. Chondrites and their components. *Treatise on geochemistry*
593 1, 711.

594 Shu, F.H., Shang, H., Lee, T., 1996. Toward an astrophysical theory of chondrites. *Science*

595 (80-). 271, 1545–1552.

596 Skinner, W.R., Leenhouts, J.M., 1993. Size distributions and aerodynamic equivalence of
597 metal chondrules and silicate chondrules in Acfer 059, in: Lunar and Planetary Science
598 Conference.

599 Teitler, S.A., Paque, J.M., Cuzzi, J.N., Hogan, R.C., 2010. Statistical tests of chondrule
600 sorting. *Meteorit. Planet. Sci.* 45, 1124–1135.

601 Uesugi, M., Sekiya, M., Nakamura, T., 2008. Kinetic stability of a melted iron globule during
602 chondrule formation. I. Non-rotating model. *Meteorit. Planet. Sci.*
603 <https://doi.org/10.1111/j.1945-5100.2008.tb00680.x>

604 Urey, H.C., 1952. Chemical fractionation in the meteorites and the abundance of the
605 elements. *Geochim. Cosmochim. Acta* 2, 269–282.

606 Wang, Y., Hua, X., WeiBiao, H., 2007. Petrogenesis of opaque assemblages in the Ningqiang
607 carbonaceous chondrite. *Sci. China Ser. D Earth Sci.* 50, 886–896.

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611 Figures:

612

613 Figure 1: (a) Aluminum witness plate and target after the impact experiment. (b) High-speed
614 video image before impact. Projectile is elongated along the trajectory due to exposure
615 duration (0.5 μ s). (c) High-speed video image during the post impact blast (\sim 14 μ s after
616 impact)

617

618 Figure 2: BSE-SEM images of the aluminum ejecta catcher showing the 13 ejecta analyzed
619 (iron metal bead in white).

620

621 Figure 3: BSE-SEM images of 9 chondrules of Yamato 81020, including metal beads (in
622 white).

623 Figure 4: Cumulative size frequency of (a) chondrules in CO chondrites (data from Rubin,
624 1989 transformed into a theoretical three-dimensional size distribution after a Saltykov
625 analysis; $n = 2334$) ; (b) ejecta from hypervelocity experiment ($n = 9326$), (c) metal
626 beads in chondrules of Yamato 81020 transformed into a theoretical three-dimensional
627 size distribution after a Saltykov analysis ($n = 3517$; dotted line = individual analyses in
628 the nine chondrules shown in Figure 3, bold line = mean), (d) metal beads in ejecta
629 ($n = 1625$; dotted line = individual analyses in the thirteen ejecta shown in Figure 2, bold
630 line = mean).

631 Figure 5: Size frequency of chondrules in CO chondrules (data from Rubin, 1989 transformed
632 into a theoretical three-dimensional size distribution after a Saltykov analysis, $n = 2834$),
633 ejecta from hypervelocity experiment ($n = 9326$), metal beads in chondrules of Yamato
634 81020 transformed into a theoretical three-dimensional size distribution after a Saltykov
635 analysis ($n = 3517$) and metal beads in ejecta ($n = 1625$).









