The quasi-universality of chondrule size as a constraint for chondrule formation models

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Abstract

Primitive meteorites are dominated by millimeter-size silicate spherules called chondrules. The nature of the high-temperature events that produced them in the early solar system remains enigmatic. Beside their thermal history, one important clue is provided by their size which shows remarkably little variation (less than a factor of 6 for the mean chondrule radius of most chondrites) despite the extensive range of ages and heliocentric distances sampled. It is however unclear whether chondrule size is due to the chondrule melting process itself, or has been simply inherited from the precursor material, or yet results from some sorting process. I examine these different possibilities in terms of their analytical size predictions. Unless the chondrule-forming “window” was very narrow, radial sorting can be excluded as size-determining processes because of the large variations it would predict. Molten planetesimal collision or impact melting models, which derive chondrules from the fragmentation of larger melt bodies, would likewise predict too much size variability by themselves; more generally any size modification during chondrule formation is limited in extent by evidence from compound chondrules and the considerable compositional variability of chondrules. Turbulent concentration would predict a low size variability but lack of evidence of any accretion bias in carbonaceous chondrites may be difficult to reconcile with any form of local sorting upon agglomeration. Growth by sticking (especially if bouncing-limited) of aggregates as chondrule precursors would yield limited variations of their final radius in space and time, and would be consistent with the relatively similar size of other chondrite components such as refractory inclusions. This suggests that the chondrule-melting process(es) simply melted such nebular aggregates with little modification of mass.

Keywords: Meteorites, Solar nebula, Cosmochemistry, Disk, Accretion

1. Introduction

Primitive meteorites, or chondrites, bear witness to the birth of the solar system, 4.57 billion years ago, when the infant Sun was surrounded by a gaseous protoplanetary disk. Beside the refractory inclusions—the earliest solids of the solar system (e.g. MacPherson 2005)—, chondrites are mostly composed of millimeter-size silicate spherules called chondrules (Connolly and Desch 2004). They appear to result from the solidification of molten droplets following short (< hours or days at most) high-temperature events (e.g. Hewins et al. 2005) which must have occurred repeatedly during the evolution of our protoplanetary disk (Jones 1996). Indeed their estimated ages vary in a time span of 0-3 Ma after the formation of refractory inclusions (Villeneuve et al. 2009, Connolly et al. 2012).

Despite their ubiquity, the formation mechanism of chondrules, presumably a prominent process in the protoplanetary disk, is still heavily controversial. “Planetary” scenarios currently investigated involve impact-induced melting, similar to those invoked for crystalline lunar spherules (Symes et al. 1998, Sears 2005), or the collision between already molten planetesimals (Sanders and Scott 2012, Asphaug et al. 2011). Objections against such scenarios include the lack of correlation of chondrules with other expected impact effects, their essentially chondritic bulk composition, their old but variable ages, etc. (see e.g. Taylor et al. 1983). In the last decades, attention has thus focused on “nebular” scenarios, where chondrules are interpreted as the products of flash-heating of nebular precursors (e.g. “dustballs”). While the X-wind model flinging chondrules produced at the inner disk edge outward (Shu et al. 2001, Hu 2010) appears to have fallen out of favor (Desch et al. 2010), formation by shock waves, due either to gravitational instabilities (Boss and Durisen 2005) or eccentric planetary embryos (Morris et al. 2012) is still a leading contender, with formation in short circuits in magnetohydrodynamical turbulence (McNally et al. 2013) or in disk winds (Salmeron and Ireland 2012) being also more recently considered. A serious drawback of these nebular scenarios, though, is the observed retention by chondrules of significant amounts of moderately volatile elements such as Na (Alexander et al. 2008, Hewins et al. 2012), suggestive, unless chondrules cooled in tens of seconds (e.g. Rubin 2000), of high partial pressures of these in chondrule-forming regions, possibly because of high concentrations of the partially evaporating chondrules themselves—in any case difficult to reconcile with current disk models. Chondrule formation is obviously not a settled issue, nor can the above do justice to all proposed ideas—we refer the interested reader to Boss (1996), Jones et al. (2000), Desch and Connolly (2002), Krot et al. (2009), Desch et al. (2012).

While most studies have concentrated on the thermal history of chondrules, their sizes also constitute an important con-
straint. Beyond the absolute scale (~0.1-1 mm), a striking property of the mean chondrule sizes vary little in single meteorites (being mostly within a factor of 2 of the mean), e.g. King and King (1978), Eisenhour (1996), Kuebler et al., 1999; Nelson and Rubin (2002), but the mean chondrule size of individual chondrules spans a limited range of less than a factor of 6 across all chemical groups (setting aside the CH (10-45 mm) and CB (2.5 mm for the CB subgroup) chondrites, as these petrographically very distinctive chondrites likely had anomalous geneses (Krot et al., 2005)). There is moreover little systematic behavior, e.g. as to carbonaceous versus noncarbonaceous chondrites (Benoi et al., 1999; Scott and Krot 2003). This is especially striking given the wide range of chondrule ages or the range of reservoirs that seems required by petrographic specificities of chondrules in different chondrite groups (Jones, 2012), from which order-of-magnitude variations of many potentially controlling astrophysical parameters (e.g. density, turbulence etc.) could be expected. Whichever process determined chondrule size was thus remarkably insensitive to these variations.

The quasi-universality of chondrule size should thus be an important discriminant among different chondrule-forming theories. However, it is a priori unclear whether chondrule size was acquired during the chondrule-melting event itself (e.g. Benoit et al., 1999; Kadono et al., 2008; Asphaug et al., 2011), or was simply inherited from the precursor (Sekiya, 1997; Zsom et al., 2010), or yet was a result of some sorting process (Cuzzi et al., 2001). In this paper, I thus examine the effects on chondrule size of the different possible stages in the chondrule cycle, and in particular focus on whether the small variability of mean chondrule size among chondrites can be reproduced. Although chondrule size has been previously addressed as part of specific chondrule- or chondrite-forming scenario developments (e.g. Cuzzi et al., 2001; Susa and Nakamoto, 2002; Miura and Nakamoto, 2005; Asphaug et al., 2011), this is the first attempt at a comprehensive theoretical examination of this question. After a presentation of the overall “philosophy” and notations in Section 3, I present and discuss size predictions of processes related to precursor growth (Section 4), melting (Section 5) and transport (Section 6). In Section 7, I summarize and conclude.

2. Generalities

Schematically, the “lifecycle” of a chondrule in the protoplanetary disk, prior to incorporation in a chondrite, involves three broad categories of processes:

(i) The growth of chondrule precursors, limited by fragmentation or bouncing (Section 4).

(ii) Chondrule formation proper, which may involve simple melting of preexisting solids, fragmentation of larger melt bodies and/or coagulation of smaller ones (Section 4).

(iii) The transport of chondrules/chondrule precursors in the gas and possible associated sorting, either globally (disk-wide) or locally (Section 5).

These are depicted in Fig. 1. Depending on the appropriate chondrule formation scenario, a given chondrule/chondrule precursor may have undergone part or all these different stages in various, possibly repeatable sequences until its incorporation in a chondrite. For example, a particular chondrule precursor may have first grown, then melted in a chondrule-forming event, have undergone aerodynamic transport, be remelted in a second chondrule-forming event, before another transport phase and accretion in a planetesimal.

Each of these stages may have left a “fingerprint” (Cuzzi and Weidenschilling, 2006) on the size distribution of the final chondrules, so in general the shape of the size distribution will result from a complex superposition of several processes. Nevertheless, the well-defined peaks in the observed chondrule size distributions in chondrites (e.g. Teller et al., 2010) are unlikely to be the coincidental result of several processes so that the mean size of chondrules in a given chondrite should be essentially traceable to one single process. Since, as already emphasized, chondrule mean size does not vary much among different chondrite groups, it would appear that essentially one single process determined that chondrule mean size for all chondrites. This does not exclude that chondrules in different chondrite groups may have undergone qualitatively different mechanisms affecting chondrule size, but these would be order unity effects.

The purpose here is to seek the process which determined the typical size of chondrules in the different chondrites, which I will refer to as the size-determining process for short. In the upcoming sections, I will discuss processes relevant to the above stages and express the chondrule size they predict by themselves with simple analytical formulas (including some already available in the literature). As argued above, I will mostly not address the whole size distribution information, which, although richer than the mere datum of the mean size, is a priori...
3. Chondrule precursor growth

Chondrules are widely believed to result from the melting of preexisting solids called “precursors”. In that case, a first possibility is that chondrule size is inherited from them and thus dictates by the primary coagulation process of solid grains (Sekiya 1997; Zsom et al. 2010; Chokshi et al. 2003; Dominik and Tielens 1997; Blum and Wurm 2008; Gutierrez et al. 2010). In inner regions of the protoplanetary disk, growth is likely to be limited by a velocity threshold for sticking rather than by inward drift (Birnstiel et al. 2012).

For many limiting processes (e.g. Gutierrez et al. 2010; Beitz et al. 2011), the critical sticking velocity can be cast in the form:

\[ \Delta v = \nu_{\text{ref}} \left( \frac{m_p}{m_*} \right)^{-\delta} \]  

where \( m_p \) is the aggregate mass and \( m_*, \nu_{\text{ref}}, \delta \) fixed parameters.

In a turbulent disk, the particle-particle velocity may be approximated by:

\[ \Delta v = \max \left( \Delta t \frac{||\nabla P||}{\rho}, \sqrt{ac_s} \min \left( \frac{Re^{1/4}}{\Omega \Delta t}, \sqrt{3} \Omega \Delta t \right) \right) \]  

where \( \Delta t \) is the absolute difference in stopping time (due to finite dispersion (in size and shape), assumed here to be of order \( \tau \) and \( ||\nabla P|| \) is the euclidean norm. The first contribution is meant to be that of the background pressure gradient (for \( \tau \ll \Omega^{-1} \), Youdin and Goodman 2005), while the second one is that of turbulent fluctuations (using approximations in section 3.4 of Ormel and Cuzzi 2007) for \( \tau \) smaller and larger than the Kolmogorov timescale \( Re^{-1/2} \Omega^{-1} \), respectively, where

\[ Re = \frac{ac_s H}{v_{\text{mol}}} = 2 \sqrt{2} \frac{\Sigma \tau H^* \alpha}{m} \]  

is the Reynolds number, with \( v_{\text{mol}} \) the molecular kinematic viscosity of the gas and \( \sigma H = 5.7 \times 10^{-20} \) m²/s the collisional cross section of \( H_2 \) (Cuzzi et al. 2001).

The size resulting from growth by sticking is then obtained by equating the particle-particle velocity (3) and the critical sticking velocity (2). Expressed in term of the compact-equivalent radius \( a_{\text{comp}} \equiv a \delta^{1/3} \phi \) with \( \phi \) the volume filling factor, this size is given by:

\[ a_{\text{comp}} = \min \left( \frac{2}{\pi} \frac{\tau}{\Delta t} \frac{v_{\text{ref}}}{\nu_{\text{ref}}} \left( \frac{3m_p}{4\pi} \frac{\Sigma}{H_{\text{in}}P_{\|}} \right)^{1/3(1+\delta)} \right) \]  

\[ \max \left( \frac{\tau}{\Delta t} \frac{v_{\text{ref}}^2}{\nu_{\text{ref}}^2} \left( \frac{3m_p}{4\pi} \frac{\Sigma}{\alpha} \right)^{3/4} \left( \frac{m}{\alpha H_{\text{c}}} \right)^{3/4} \right) \]  

\[ \left( \frac{v_{\text{ref}}}{c_s} \right)^2 \left( \frac{3m_p}{4\pi} \frac{\Sigma}{3\alpha H_{\text{c}}} \right)^{2/3} \frac{2}{\nu_{\text{ref}}^2} \left( \frac{\Sigma}{\alpha} \right)^{1/6} \]  

with \( \rho_\delta \) meant to be the compact density (set at \( 3 \times 10^3 \) kg/m³).

With this general formula at hand, we now examine the specific cases of fragmentation- and bouncing-limited regimes.

3.1. Fragmentation-limited growth

Fragmentation is generally modeled with a size-independent (\( \delta = 0 \)) velocity threshold \( \nu_{\text{ref}} \approx 1 - 10 \) m/s (e.g. Gutierrez et al. 2010; Birnstiel et al. 2012). The stopping time would be in the inertial range of the Kolmogorov cascade, yielding:

\[ a_{\text{comp}} = \frac{2}{3\pi \rho_\delta H^{2/3} \alpha} \left( \frac{v_{\text{ref}}}{c_s} \right)^2 = 0.7 \text{ mm} \left( \frac{\Sigma}{10^2 \text{ kg/m}^2} \right)^{1/3} \left( \frac{\nu_{\text{ref}}}{1 \text{ m/s}} \right)^2 \left( \frac{300 \text{ K}}{T} \right)^{1/2}. \]  

Although protoplanetary disk physics are not well-understood, for evolution times of a few Ma, and heliocentric distances spanning say 1-5 AU at least, variations of \( \Sigma \) and \( \alpha \) by at least 1-2 orders of magnitude each may be robustly expected (e.g. Hayashi 1981; Desch 2007; Chambers 2009; Turner et al. 2010; Yang and Ciesla 2012; Flock et al. 2011). Thus, unless chondrule formation took place on a temporally and spatially very narrow window, it appears that a fixed fragmentation threshold

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1. If \( \Delta t \ll \tau \) (unlike what I assume here), a significant error will be incurred if the stopping time corresponding to the second line of equation (5) is not explicitly constrained to be smaller than \( Re^{-1/2} \Omega^{-1} \).
would predict too much variation of chondrule size by itself to be the size-determining process.

There is however evidence that fragmentation velocity may depend on size. Experiments by \textit{Beitz et al.} (2011) suggest \( \delta = 0.158 \) and \( m_* = 3.67 \times 10^4 \) kg for \( \nu_{\text{ref}} = 1 \) cm/s (see also Windmark \textit{et al.} (2012b)). In that case, the size (still corresponding to a stopping time in the inertial range) becomes:

\[
\alpha_{\text{comp}} = 0.6 \text{ mm} \left( \frac{\Sigma}{10^4 \text{ kg/m}^2} \right) \left( \frac{10^{-3} \text{ 300 K}}{\alpha} \right)^{0.51} \phi^{-0.32}. \tag{7}
\]

With a reduced dependence on \( \Sigma/\alpha \) (now to the 0.51 power), this could satisfy the chondrule size variability constraint.

### 3.2. Bouncing-limited growth

Particles may bounce at velocities much lower than the fragmentation limit (Zsom \textit{et al.} 2010), which may thus set the real limit to growth.4 Although numerical simulations of aggregate collisions have hitherto failed to reveal this “bouncing barrier” for porous aggregates—the expected products of initial hit-and-stick growth—(e.g. Seizinger and Kley 2013), Kothe \textit{et al.} (2013) experimentally found a bouncing velocity parameterized by \( \delta = 3/4 \) and \( m_* = 10^{-7.5} \) kg for \( \nu_{\text{ref}} = 1 \) cm/s, yielding a limiting size of:

\[
\alpha_{\text{comp}} = \min \left(0.3 \text{ mm} \left( \frac{\Sigma}{10^4 \text{ kg/m}^2} \right)^{\frac{1}{2}} \left( \frac{\Delta \tau/\tau_{\text{comp}}}{\nu_{\text{ref}}} \right)^{\frac{1}{2}} \left( \frac{0.1}{\tau} \right)^{\frac{1}{3}} \left( \frac{300 \text{ K}}{\tau} \right)^{\frac{1}{2}} \right),
\]

\[
\max \left(0.1 \text{ mm} \left( \frac{\Sigma}{10^4 \text{ kg/m}^2} \right)^{\frac{1}{3}} \left( \frac{1}{\tau} \right)^{\frac{1}{3}} \left( \frac{300 \text{ K}}{\tau} \right)^{\frac{2}{3}} \left( \frac{\tau}{\Delta \tau} \right)^{\frac{1}{3}} \right),
\]

\[
0.08 \text{ mm} \left( \frac{\Sigma}{10^4 \text{ kg/m}^2} \right)^{\frac{1}{3}} \left( \frac{10^{-3} \text{ 300 K}}{\alpha} \right)^{\frac{2}{3}} \left( \frac{0.1}{\tau} \right)^{\frac{1}{3}} \right)
\]

So depending on the relevant regime, we obtain dependences in \( \Sigma^{1/3}, (\Sigma/\alpha)^{2/3} \) or \( \Sigma^{1/11} \). To get a sense of the sensitivity of that result to the uncertainties of the bouncing barrier, we note that for theoretical thresholds discussed by Gütter \textit{et al.} (2010), the exponents would become respectively 2/5, 3/10 and 1/4 for “hit-and-stick growth” (“S1”; \( \delta = 1/2 \)) and 6/11, 9/22 and 3/8 for “sticking with surface effects” (“S2”; \( \delta = 5/18 \)). These are weak dependences (a range of 0.18-0.41). This is because the positive and negative dependences of the relative velocity (equation (5)) and the sticking velocity (equation (2)), respectively, add up when these are equated to each other, hence a weak dependence of size on disk parameters after solving for it.

The result also weakly depends on the porosity of the aggregates, so long the initial increase due to fractal growth has been checked e.g. by compression at moderate collision speeds (e.g. Ormel \textit{et al.} 2007, Zsom \textit{et al.} 2010). However, porosity evolution models by Okuzumi \textit{et al.} (2009), whose numerical experiments show greater porosity increases in unequal-sized collisions than modeled by Ormel \textit{et al.} (2007), lead to spectacular decreases of \( \phi \) by more than 3 orders of magnitude, and the bouncing barrier (not included) may be less stringent for such aggregates (Kothe \textit{et al.} 2013). However, very low \( \phi \) are probably unrealistic—in fact, pre-compaction estimates for fine-grained rims around Allende chondrules, presumably accreted in the disk, are 20-30 \% (Bland \textit{et al.} 2011)—because not all monomers were micron-sized, which would have placed lower bounds on the overall density and stopping times (and possibly affected sticking properties (Ormel \textit{et al.} 2008, Beitz \textit{et al.} 2012)). Indeed, the compositional variability of chondrules (Hezel and Palme 2007) indicate that chondrule precursors contained coarse grains (\( \gtrsim 10-100 \mu \text{m} \)), e.g. refractory inclusions or earlier chondrule debris, as sometimes evidenced by relict grains (Jones 1996). The precursors may have been analogous to agglomeratic olivine objects or amoeboid olivine aggregates found in chondrites (Ruzicka \textit{et al.} 2011, 2012), both of probable nebular origin. The overall similarity in size (within a factor of a few) of the latter with chondrules would be also consistent with a derivator of chondrule size from nebular aggregates, although the systematically smaller size of refractory inclusions would have yet to be explained (e.g. different available time, monomer size, temperature...).

In the above, we have considered only typical collision speeds to estimate the final size, but especially for the turbulent contribution, a distribution of velocities would be more realistic, and particles may grow beyond the bouncing barrier calculated above through a series of low-probability, low-velocity collisions (e.g. Windmark \textit{et al.} 2012a, Garaud \textit{et al.} 2013). While meter-size particles would be very rare, the effective “bottleneck” of the coagulation may be increased above our nominal bouncing barrier, and would be asymptotically determined by a balance between sticking and fragmentation probabilities (Windmark \textit{et al.} 2012a) and Garaud \textit{et al.} (2013), both finding a shift of one order of magnitude, did not take into account the decrease of the bouncing speed with increasing size (not to mention possible increased fragmentability), and their assumption of a Maxwellian distribution may overestimate the low-velocity tail (susceptible to sticking) of the true distribution at the expense of the high-velocity one (susceptible to fragmentation) (Pan and Padoan 2013), both of which effects would lead not only to a decrease of the asymptotic limit, but also to a steep increase of the time needed for growth (inversely proportional to the sticking probability) beyond our nominal bouncing barrier. Still, the “lucky” sticking events could account for the large-size tail of chondrule size distributions.

### 4. Chondrule melting

Certainly, the cornerstone of the lifecycle of chondrules is the chondrule-melting mechanism itself. Although it might have merely melted preexisting aggregates, molten bodies could have fragmented or coagulated, hence a size modification between the precursors and the chondrules, as I envision now.
4.1. Simple melting of precursor

I call “simple melting” a scenario where chondrule size (or more properly, mass) is inherited from the precursors, without significant mergers or disruptions. This is generally implied in the conventional “flash-heating” picture of many “nebular” scenarios, e.g. shockwave (Desch et al. 2005), X-wind (Shu et al. 2001), lightning (Desch and Cuzzi 2000) or short circuits in magnetorotational turbulence (McNally et al. 2013).

Simple melting scenarios would not be expected to leave any fingerprint on chondrule size distribution, unless the mechanism responsible somehow preferentially processed solids from one size bin, or destroyed the solids from other size bins. The model closest to the former situation known to me seems to be the recent Salmeron and Ireland (2012) scenario of chondrule formation in disk winds, where only particles of a specific size bin are small enough to be first entrained upward and big enough to then fall back (because of dust accretion), whereupon gas drag leads to melting. For the time being, no expression of this preferred size as a function of disk parameters is available. As to selective destruction, investigators of the shockwave models have also proposed that large droplets would get disrupted by the ram pressure appearing upon crossing the shock front (Susa and Nakamoto 2002) while tiny ones would be evaporated (Miura and Nakamoto 2005). But the two resulting size cutoffs would not in general coincide even within a factor of a few so that the typical size of chondrules would rather be inherited from precursors than set by the shock event.

4.2. Melt fragmentation

Other scenarios envision chondrules as fragments of larger melt bodies. Two illustrative models will be considered here: the molten planetesimal collision (or “splashing”) scenario (e.g. Asphaug et al. 2011; Sanders and Scott 2012) and an hypervelocity impact plume (e.g. Symes et al. 1998).

In the splashing scenario of Asphaug et al. (2011), melt is already present in the planetesimal before collision as a result of $^{26}$Al decay. Moderate-velocity collision eject sheets of this melt which fragment as pressure unloads until the Laplace pressure $2\gamma/a$ (with $\gamma$ the surface tension) of the droplets essentially balances the original (hydrostatic) pressure in the source planetesimal prior to impact, resulting in a typical radius of

$$a = \frac{2\gamma}{GE\rho_p R_p^2}$$

with $R_p$, $\rho_p$ the radius and density of the source planetesimal, respectively, and $E$ an efficiency factor (Asphaug et al. 2011). To be the size-determining process, the splashing scenario would require the colliding bodies to have a very narrow size distribution around ~10 km (within a factor of 3), which is not borne out by that of the asteroid main belt or earlier modeled stages thereof (Davis et al. 2002; Morbidelli et al. 2009; Weidenschilling 2011).

For impact velocities $\gtrsim$ 3 km/s (Stöffler et al. 1991), melt can be produced by the impact itself (Symes et al. 1998; Benoit et al. 1999). The initial fragmentation of the liquid yields clumps of radius (Melosh and Vickery 1991), see also Johnsson and Melosh (2014):

$$a = 0.3 \text{ mm} \left( \frac{\gamma}{0.4 \text{ N/m}} \right)^{1/2} \left( \frac{R_i}{1 \text{ km}} \right)^{1/2} \left( \frac{15 \text{ km/s}}{v_i} \right).$$

While the dependence on impactor radius is weak, that scenario would predict the correlated existence of larger (~cm-size) glassy objects (equation 11), contrary to observations (although a few impact melts occur in chondrite breccias (e.g. Keil et al. 1980)). As a general problem with melt fragmentation scenarios, large chondrule-textured objects are persistently lacking (Taylor et al. 1983)—the largest chondrule known to date being the 5 cm-diameter “Golfball” in the Gunlock L3 chondrite (Prinz et al. 1988). I however note that the large CB$_3$ and small CH chondrite chondrules would match the larger size variations expected from impact, which would be consistent with the generally agreed impact-induced formation of these objects (Krot et al. 2005) which, it must be reminded, are very different from mainstream chondrules.

4.3. Droplet mergers

One could envision that currently observed chondrules result from the mergers of smaller liquid droplets. Ignoring fragmentation, the growth of chondrules would be given by

$$\frac{d}{dt} \left( \frac{4\pi}{3} \rho_d a^3 \right) = 4\pi \alpha_d^2 \rho_d \Delta v,$$

with $\rho_d$ the droplet mass density and $\Delta v$ a typical droplet-droplet velocity at time $t$. The final radius (if, ex hypothesi, the initial one can be neglected) will then be:

$$a = \frac{\rho_d}{\rho_s} \Delta v \tau_m$$

$$= 0.2 \text{ mm} \left( \frac{\rho_d}{10^{-4} \text{ kg/m}^3} \right) \left( \frac{\Delta v}{1 \text{ m/s}} \right) \left( \frac{\tau_m}{10 \text{ h}} \right).$$

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with $t_m$ the time during which droplet mergers took place.

To my knowledge, no chondrule formation model has predicted chondrule sizes this way (which would require very high solid densities). One may however empirically evaluate the importance of collisions from the abundance of compound chondrules, i.e. chondrules fused together (Gooding and Keil 1981, Wasson et al. 1995, Ciesla et al. 2004, Akaki and Nakamura 2005), whose formation differs from the mergers envisioned above only in that the fused components did not have time to relax to one spherical object. The average compound chondrule fraction in ordinary chondrites is only 4% (Gooding and Keil 1981) and may be twice higher in CV chondrites (Akaki and Nakamura 2005), suggesting that collisions were not frequent enough to significantly affect the size distribution of chondrules.

However, cooling histories may be conceivable for which the time span where compound droplets did not have time to relax to sphericity was only a small fraction of the time where mergers were complete (Alexander and Eb bel 2012). As to this possibility, an important clue is given by the fact that nonporphyritic chondrules (i.e. chondrules which have been most efficiently melted with most crystal nuclei destroyed before cooling) have a higher compound fraction (up to 28% according to Gooding and Keil (1981)) than their porphyritic counterparts. In Appendix A, I argue, with a simple modeling of compound chondrule formation, that colliding pairs involving one or two totally molten droplets may have frozen in the compound shape at higher temperatures than already crystallizing ones, which might explain why. Alternatively, nonporphyritic chondrules may have generally formed in distinct environments with higher collision rates (Gooding and Keil 1981, Ciesla et al. 2004). In either case, a size difference between nonporphyritic and porphyritic chondrules would be expected if droplet mergers significantly affected chondrule size. Such a difference does exist, with nonporphyritic chondrules being on average bigger than porphyritic ones (e.g. Rubin and Grossman 1987, Rubin 1989, Nelson and Rubin 2002, Weyrauch and Bischoff 2012), but is limited, usually within a factor of 2 (and Nelson and Rubin 2002 even suggest it to be an artifact of preferential fragmentation of large porphyritic chondrules on the parent-body), although droplet densities and/or cooling timescales may have varied by orders of magnitude. This is evidence that mergers had a marginal effect on size in general.

The variability of chondrule composition provides an independent general limitation on the importance of mergers, which also pertains to “melt fragmentation” scenarios discussed in Section 5.2 since the large melt bodies to be disrupted, or their precursors, would have had to be produced by the merger of preexisting bodies as well. Hezel and Palme (2007) showed that no more than 10-100 precursor grains could have contributed to each chondrite given the observed variances, limiting any radius change to a factor of a few. One could argue though that the compositional variability of chondrules in a given chondrite is due to the diversity of their source reservoirs. This is certainly a contribution and the cosmochemical fractionation trends exhibited by chondrules are essentially the same as those of bulk chondrites (Grossman and Wasson 1983).

But if mergers were so numerous as to homogenize chondrule compositions in each chondrule-forming region, one would expect components of compound chondrules to have very similar compositions. While bulk chemical data are currently lacking for these objects and are certainly desirable to settle the matter, differences in modal mineralogy and mineral chemistry in many of them (Wasson et al. 1995, Akaki and Nakamura 2005) make this fairly unlikely. Another problem is the existence of a sizable proportion (>10%) of chondrules with anomalous rare earth element (REE) abundance patterns (Misawa and Nakamura 1988, Pack et al. 2004) presumably inherited from refractory precursors (see e.g. Boynton 1989). Refractory inclusions, formed during $\lesssim 10^5$ years after the building of the protoplanetary disk (e.g. Bizzarro et al. 2004), presumably within a few AU of the Sun, would be rapidly mixed together before the formation of most chondrules. One would thus not expect any chondrule-forming reservoir as a whole to show such anomalous REE patterns and they have not been observed at the scale of bulk chondrites (e.g. Evensen et al. 1978, Boynton 1984). This argues against reservoir-scale compositional homogenization of grains.

Petrographical and compositional evidence from chondrules thus appears inconsistent with significant (order-of-magnitude) size modification during chondrule formation. More subordinate size modifications might however explain part of the vari- ations of chondrule size (see e.g. Rubin 2010), and perhaps the systematic size difference with refractory inclusions.

5. Transport and sorting

The age range of chondrules in single chondrites (Villeneuve et al. 2009, Connelly et al. 2012) suggests that they spent a few million years as free-floating objects in the protoplanetary disk. Aerodynamic transport may then have resulted in size sorting of chondrules or their precursors, either on a global or a local scale, as I now examine.

5.1. Global sorting

Jacquet et al. (2012) showed that the dynamic response of particles embedded in the gaseous disk was essentially gov- erned by the “gas-grain decoupling parameter” $\tilde{S} \equiv \Omega \tau /\alpha$. For $\tilde{S} \ll 1$, particles are well-coupled to the gas, while for $\tilde{S} > 1$, they tend to settle to the midplane and drift toward the Sun. If chondrules (or chondrule precursors) were produced in the inner regions of the disk and subsequently redistributed in outer regions of the disk, their outward transport would essentially be stopped at the $\tilde{S} = 1$ line (Jacquet et al. 2012). Thus, at a given heliocentric distance, particles larger than

$$a \approx \frac{2\Sigma a}{\pi \rho_s} = 0.2 \text{mm} \left( \frac{\Sigma}{10^3 \text{kg/m}^2} \right) \left( \frac{\alpha}{10^{-3}} \right) \left( \frac{3 \times 10^3 \text{kg/m}^3}{\rho_s} \right)$$

5 For example, the turbulent diffusion timescale $R^2 / (\alpha c_s^2 \Omega)$ is about $5 \times 10^5$ years for $R = 1$ AU, $T = 1500 \text{ K}$, $\alpha = 10^{-3}$. 

6
would have been prevented from reaching this location so that equation (15) would provide a maximum cutoff. Although $\Sigma$ and $\alpha$ may be anticorrelated, e.g. in a steady disk or a dead zone (e.g. Fleming and Stone 2003; Terquem 2008), this would not prevent order-of-magnitude variations to arise (Jacquet et al. 2012), contrary to observations. Radial transport in the disk is thus unlikely to have been the size-determining process.

Solids may have been transported in winds rather than through the disk. In the X-wind scenario, the chondrules transported to the planet-forming region (rather than falling back close to the X point or flying toward interstellar space) must have a stopping time comparable to the orbital period at the X point (Shu et al. 1996). This would however require these dusty aggregates to have already exhibited some chondrule size selection, thus establishing prior to photophoretic transport.

5.2. Local sorting

Sorting could alternatively have been local, perhaps as a prelude to planetesimal formation. Cuzzi et al. (2001) proposed that turbulence concentrated particles between eddies, most efficiently for stopping times equal to the Kolmogorov timescale, corresponding to a radius of

$$a = \frac{2^{1/3}}{\pi \rho_s} \left(\frac{\Sigma}{\alpha \mu_s}\right)^{1/2} = \frac{0.1 \text{ mm}}{\left(\frac{3 \times 10^3 \text{ kg/m}^3}{\rho_s}\right)^{1/3} \left(\frac{10^{-3} \text{ Am}^2}{\mu_s}\right)^{1/2}}$$

The thus concentrated particles could pave the way to planetesimal formation (Cuzzi et al. 2001; 2010) and/or provide the dense environment required for chondrule formation (Cuzzi and Alexander 2006), which would thus account for the preferred chondrule size. Other proposed accretion processes such as the streaming instability (Youdin and Goodman 2005; Johansen et al. 2007; 2009; Bai and Stone 2010; Jacquet et al. 2011) may also be accompanied by some size sorting but this has not been investigated to date.

The $(\Sigma/\alpha \mu_s)^{1/2}$ dependence predicted by the turbulent concentration scenario is comparable to that of precursor growth by sticking (if somewhat stronger than for bouncing-limited growth). It is notable that the detailed size distribution predicted by turbulent concentration would match the observed size (or more precisely here, $\rho_s \alpha$) distribution of chondrules in ordinary chondrites (Cuzzi et al. 2001; Teitler et al. 2010), although that depends on the assumed pre-sorting distribution. It would also be consistent with rough aerodynamical equivalence of other components (Hughes 1978; 1980; Skinner and Leenhouss 1993; Kuebler et al. 1999).

However, this equivalence is far from perfect, with e.g. metal grains (Schneider et al. 1998; Nettles and McSween 2006) or refractory inclusions (May et al. 1999; Hezel et al. 2008) having generally smaller $\rho_s \alpha$ than the colocated chondrules, and the size difference between porphyritic and nonporphyritic chondrules, not to mention the dust that formed the matrix. We show in Appendix B that taking into account nonspherical shapes only decreases the stopping time for a given volume and thus widens the discrepancy. As a result, the very size-selective turbulent concentration would be expected to introduce a change in the proportions of components accreted relative to those present in the original reservoir: this is what Jacquet et al. (2012) called “accretion bias”. However, while such sorting could account for metal/silicate fractionation in noncarbonaceous chondrites (e.g. Zanda et al. 2006), carbonaceous chondrites (e.g. Palme and Jones 2005; Ebel et al. 2008) show little evidence of such an accretion bias, as they display near solar Fe/Si and Mg/Si ratios, and also supersolar Al/Si ratios—indicating, if anything, an overabundance of refractory inclusions rather than an undersampling due to non aerodynamical equivalence. This makes any kind of syn-accretional local sorting difficult to envision for the bulk of chondrule accretion.

It is important to note, though, that the complementarity between chondrules and matrix, which control the Mg/Si ratio

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6We note that, regardless of where chondrules were produced, vertical settling would concentrate particles larger than this same size (roughly) at the midplane. Settling and radial segregation could act together to narrow the size distribution around the size given.

7The numerical factors differ slightly from those of Cuzzi et al. 2001 because of the typical density I have chosen.

8With the exception of type B refractory inclusions in CV chondrites, which are on the contrary larger (mm-cm) than neighbouring chondrules.
(Hezel and Palme 2010), could be ensured in a local sorting scenario if the grains constituting the matrix accreted on the individual chondrules prior to sorting, provided (i) the bulk of the dust did end up captured that way and (ii) the amounts accreted were proportional to chondrule mass, for which there is both empirical (Metzler et al. 1992) and theoretical (Ormel et al. 2008) support. In this case, size selection of the dust-coated chondrules (which would amount to a size selection of the embedded chondrules, modulo a constant factor) would not affect the (complementary) chondrule-to-matrix ratio. This would not however explain the overabundance of refractory inclusions in carbonaceous chondrites, unless the size distribution of the former was modified after accretion (similar to the suggestion of Nelson and Rubin 2002) for some chondrules. Note that these arguments against syn-accretional sorting would not apply to sorting prior to or during chondrule formation (as suggested by Morris et al. 2012 for the bow shock model), provided it was temporally distinct from chondrite accretion.

### 6. Summary and conclusions

I have investigated the origin of the weakly variable size of chondrules in chondrites. To that end, I have reviewed possible stages in the lifecycle of chondrules and their precursors, as broadly divided in: chondrule precursor growth, chondrule melting and sorting during aerodynamic transport. For these different processes, I have expressed analytically the preferred chondrule size they would produce. Although I have strived to be as comprehensive as possible, I make no claim of completeness, nor should the formulas given be viewed as the definitive predictions of theories often still in development. Nonetheless, as they stand, they lend themselves to interesting evaluations against the meteoritical record. Indeed, although the processes envisioned were virtually all able to reproduce chondrule size for plausible values of the controlling parameters, few of them can, in their current state, account for the small variations of mean chondrule size among chondrite groups (excepting the outlying, and otherwise anomalous CH and CB groups).

I first examined the growth of potential chondrule precursors in the disk. Unless the chondrule- or chondrite-forming window was much narrower than suggested by age dating and petrographic evidence, fragmentation-limited growth of precursors would predict too wide variations to possibly be the size-determining process if the fragmentation velocity was constant, but could satisfy the constraint if the fragmentation velocity decreases with size as found by Beitz et al. (2011), yielding a \((\Sigma/\alpha)^{0.71}\) dependence. Bouncing-limited growth, while still fraught with theoretical uncertainties, would quite robustly yield limited size variability (depending on the model and the disk parameters, dependences on surface densities would be to the 0.18-0.41 power), because of the opposite size dependences of the maximum sticking velocity and the collision velocities in the turbulent disk. It would be consistent with the comparable, albeit generally smaller, size of refractory inclusions.

I then considered chondrule-melting processes themselves. Scenarios involving melt fragmentation like “splatting” melting (Sandres and Scott 2012; Asphaug et al. 2011) or impact melting (Symes et al. 1998) were also found to predict too much variability (although they may account for the anomalously sized chondrules of the CH and CB groups). This would not per se rule out these scenarios as chondrule-producing, but, unless the size predictions undergo revision, chondrule sizes would have to result from some postformational aerodynamic sorting (but see below). Based on empirical evidence from compound chondrules, droplet mergers were found to have a subordinate influence on the chondrule size distribution. The considerable compositional variability of chondrules would quite generally limit the size modifications that occurred during chondrule formation to less than a factor of a few.

I finally considered aerodynamic transport. Size sorting by radial transport would likely produce too much variability to qualify as the size-determining process. Turbulent concentration would predict likely suitably low variability (in \(\Sigma/\alpha^{1/2}\)), but lack of evidence of any accretion bias in carbonaceous chondrites argues against this and other synaccretional sorting having influenced chondrule size—although sorting may have occurred in chondrule-forming regions.

Based on the above considerations, I infer that chondrule size was inherited from the precursors (similarly to previous suggestions by Sekiya (1997), Zsom et al. (2010)). Given the considerable uncertainty around growth by sticking (e.g. Ormel et al. 2007; Okuzumi et al. 2009; Beitz et al. 2011; Windmark et al. 2012a; Garaud et al. 2013; Kothe et al. 2013), this preference relies less on confidence in the estimate of the outcome of growth by sticking herein than on a process of elimination of other competing mechanisms, because of size variability and/or independent cosmochemical arguments, and as such invites caution. If our inference were to hold true, however, chondrule-forming mechanisms would be constrained to involve simple melting of preexisting solid precursors, much like the conventional “flash-heating” picture, with little modification of size of the droplet (within a factor of a few). This would not necessarily imply that the cosmic setting of chondrule formation was “nebular” in a narrow (planetaryesimal-free)

Table 1: Summary of chondrule size models. (The reader is referred to the text for the definition of symbols and numerical applications).

| Category         | Process name               | Predicted radius                                                                 |
|------------------|----------------------------|----------------------------------------------------------------------------------|
| Precursor growth | fragmentation-limited      | \(\left(\frac{2\alpha m^2}{\rho v^2}\right)^{2/3}\) \(\left(\frac{\Sigma/m}{\alpha}\right)^{2/3}\) |
|                  | bouncing-limited           | \(\frac{2\pi m}{\rho v}\) \(\frac{\Sigma/m}{\alpha}\) \(\frac{1}{2}\)           |
| Transport        | radial sorting             | \(\frac{2\pi m}{\rho v}\) \(\frac{\Sigma/m}{\alpha}\) \(\frac{1}{2}\)           |
|                  | X wind                     | \(\frac{2\pi m}{\rho v}\) \(\frac{\Sigma/m}{\alpha}\) \(\frac{1}{2}\)           |
| Chondrule melting| splashing                  | \(\frac{2\pi m}{\rho v}\) \(\frac{\Sigma/m}{\alpha}\) \(\frac{1}{2}\)           |
|                  | impact melting             | \(\frac{2\pi m}{\rho v}\) \(\frac{\Sigma/m}{\alpha}\) \(\frac{1}{2}\)           |
|                  | droplet mergers            | \(\frac{2\pi m}{\rho v}\) \(\frac{\Sigma/m}{\alpha}\) \(\frac{1}{2}\)           |
sense, especially given evidence of large pressures and/or solid densities there (Alexander et al. (2008); see e.g. Morris et al. (2012)) but this would not fare well with the "planetary" scenarios envisioned above in their current state. Beyond the chondrule melting itself, chondrule size would also be a constraint for models of growth by sticking as indicating its outcome, and hence for models of further stages of primary accretion.

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Appendix A. A model of compound chondrule formation

I propose here a simplified model of the collision between two droplets of equal radius \(a\) and the complete or incomplete relaxation of the newly formed object to sphericity.

I restrict attention to temperatures where the plastic (viscous) behavior of chondrules wins over the elastic behavior, where collisions may result in mergers (Ciesla et al. (2004)). The transition temperature would presumably be near the glass transition temperature (around 1000 K; see Alexander and Ebel (2012)) or at any rate below 1400 K from the Connolly et al. (1994) experiments. Considering head-on collision trajectories for simplicity, the penetration length \(x\) of the droplets into each other obeys Newton’s second law:

\[
m_x \frac{d^2 x}{dt^2} = A_{contact}(x) \sigma_{xx}
\]

(A.1)

with \(m_x = (1/2) 4 \pi \rho_x a^3/3\) the reduced mass of the two colliding droplets, \(A_{contact}(x) \approx 2 \pi a(x/2)\) the contact area between the two (for \(x < a\)) and \(\sigma_{xx}\) the xx component of the (viscous) stress tensor which I approximate as \(-\gamma (dx/dt)/a\) with \(\gamma\) the droplet viscosity. Then, upon integrating the above, one finds that the two colliding droplets will come to rest (\(dx/dt = 0\)) for

\[
x = \frac{2}{a} \left( \frac{\rho_x a \Delta v}{\gamma_d} \right)^{1/2},
\]

(A.2)

with \(\Delta v\) the initial relative velocity. For \(\rho_x a = 1 \text{ kg/m}^2\) and \(\Delta v \lesssim 1 \text{ m/s}\), \(\rho_x a \Delta v \lesssim 1 \text{ Pa.s}\), much smaller than melt viscosities for \(T \lesssim 1700-2000 \text{ K}\) (Giordano et al. 2008). Thus except perhaps for temperatures close to the liquidus, I have \(x/a < 1\) (consistent with our assumption), so that the immediate result of the collision itself will be a bilobate object.

Surface tension will however tend to restore a spherical shape. The relaxation timescale is (Gross et al. 2013)

\[
t_{ph} = \alpha \gamma_d/\gamma.
\]

(A.3)

with \(\gamma\) the surface tension (taken to be 0.4 N/m). With decreasing temperature, the melt viscosity increases by orders of magnitude so that \(t_{ph}\) should eventually become longer than the cooling timescale at some temperature, below which collisions should yield compound chondrules (rather than larger spherical chondrules). For illustration, if I take the mesostasis composition of Alexander and Ebel (2012), the viscosity model of Giordano et al. (2008) and a cooling timescale of 1 h, I obtain a temperature of \(\sim 1300 \text{ K}\). In this calculation, I have taken into account the viscosity enhancement of the droplet due to suspended crystals by adopting the Roscoe (1952) formula:

\[
\eta_d = \frac{\eta}{(1 - c)^{3/2}}
\]

(A.4)

with \(\eta\) the viscosity of the pure melt and \(c\) the volume fraction of crystals taken to be 90 vol%.

Connolly et al. (1994) experimentally observed that collisions induced crystal nucleation at the interface in those droplets that were fully molten (such as those thought to solidify as nonporphyritic chondrules), and indeed most compound chondrules exhibit optical continuity at the junction (Wasson et al. 1995). For sufficient undercooling upon collision, crystal growth may have been sufficiently fast to prevent relaxation to sphericity at temperatures above the preceding threshold.

To quantify this, I adopt the crystal growth velocity \(Y\) in the interface-controlled regime of Kirkpatrick (1975):

\[
Y = \frac{\frac{f k_B T}{3 \pi \eta \sigma_0} (1 - e^{-A/k_b T})}{x}
\]

(A.5)

with \(a_0\) the molecular diameter (for which I adopt 0.27 nm—the edge of the silicate tetrahedron), \(f\) the fraction of sites available for attachment (which I set to 1), and \(A\) the chemical affinity of the crystallization reaction. I consider that the bilobate compound shape is frozen in if crystals can grow to a size \(s\) within the relaxation timescale, that is if

\[
\frac{Y t_{ph}}{x} = \frac{a f k_B T}{x 3 \pi \gamma_d \sigma_0} (1 - e^{-A/k_b T}) \gtrsim 1
\]

(A.6)

Approximating the affinity as \(A = L_c (T_L - T)/T_L\) (Kirkpatrick 1975) with \(T_L\) the liquidus temperature and \(L\), the latent heat of crystallization \((1.7 \times 10^{-19} \text{ J per silicate tetrahedron for pure forsterite})\) (Miura et al. 2010) and injecting equation (A.2) yields, after a Taylor expansion of the exponential:

\[
\frac{Y t_{ph}}{x} = \frac{1}{2} \frac{1}{\sqrt{3 \pi}} \frac{\eta}{\rho_x a \Delta v} \frac{1}{\frac{f k_B T}{3 \pi \eta \sigma_0} (1 - e^{-A/k_b T})} \frac{f L_c (T_L - T)}{\gamma_d T_L} = 6 \frac{\eta}{10^7 \text{ Pa.s}} \frac{1 \text{ kg/m}^2}{\rho_x a \Delta v} \frac{1}{(T_L - T)/T_L} \frac{1}{(T_L - T)/T_L}
\]

(A.7)

Taking the bulk type I chondrule composition of Alexander and Ebel (2012) to compute \(\eta\) with the Giordano et al. (2008) model, assuming \(T_L = 2000 \text{ K}\), the above ratio reaches unity for the chosen normalizations at \(T = 1500 \text{ K}\), higher than the limiting temperature obtained from the sole cooling time constraint.

While this treatment is quite idealized and quantitative estimates should not be taken too seriously, this does show that nonporphyritic compound chondrules can form at higher temperatures than porphyritic ones because of nucleation upon collision, and thus explain their higher frequency.
Appendix B. Epstein drag for nonspherical objects

In this appendix, I provide the expression of the drag force $F$ of the gas on a solid object much smaller than the molecular mean free path. The calculation, which ignores molecules reflected toward the object itself, and is therefore strictly valid only for convex shapes, follows the same lines than that of Dahneke (1973) although the force is here expressed in a coordinate-free vector fashion. I thus only quote the result:

$$F = \frac{\rho v_T}{4} \left( A\mathbf{u} + (1 + \beta) \int \mathbf{u} \cdot \mathbf{n} \, dA \right), \quad (B.1)$$

with $v_T = \sqrt{8kT/m}$, $dA$ the surface element vector (pointing outward) and $\mathbf{n}$ the corresponding unit vector, $A$ the integrated (not projected) surface area, $\mathbf{u}$ the mean velocity of the gas relative to the solid. The parameter $\beta = 9\pi/16$ for a perfectly nonconducting solid and $\pi \sqrt{T_p/T}/2$ for a perfect conductor (with $T_p$ the temperature of the particle). The formula assumes no rotation of the solid but the contribution of rotation would be zero if it possesses a center of symmetry (in which case the only contribution to the torque would be a braking of the rotation). If the formula is averaged over all possible orientations of the solids relative to the flow, I obtain:

$$\langle F \rangle = \frac{\rho v_T}{3} A \left( 1 + \frac{\beta}{4} \right) \mathbf{u}, \quad (B.2)$$

hence a stopping time which can be cast in the usual form

$$\tau = \frac{m_p u}{F} \equiv \frac{\rho a_{\text{drag}}}{\rho v_T (1 + \beta/4)}, \quad (B.3)$$

(where the $(1 + \beta/4)$ correction may generally be ignored), if the “aerodynamic radius” is defined as:

$$a_{\text{drag}} = \frac{3V}{A}, \quad (B.4)$$

where $m_p$ and $V = m_p/\rho_s$ are the mass and volume of the solid, respectively. This corresponds to the actual radius in the case of a sphere. For a spheroid of equatorial and polar radii $a$ and $c$, respectively:

$$a_{\text{drag}} = \frac{2c}{1 + (c/a)f(a/c)}, \quad (B.5)$$

with

$$f(x) = \begin{cases} \frac{\text{arcsinh} \sqrt{x}}{\sqrt{x}} & \text{if } x < 1 \\ \frac{\text{arcsinh} \sqrt{c}}{\sqrt{c}} & \text{if } x > 1 \\ 1 & \text{if } x = 1 \end{cases} \quad (B.6)$$

In figure B.2, $a_{\text{drag}}$ is plotted normalized to the radius of the equal volume sphere. One sees that the spherical aerodynamic equivalent of a spheroid is smaller than the latter. This is a general consequence of the isoperimetric inequality $36\pi V^2/A^3 \leq 1$. Thus, irregularly shaped inclusions aerodynamically equivalent to (spherical) chondrules should be bigger than those.

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