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Comets formed in solar-nebula instabilities! – An experimental and modeling attempt to relate the activity of comets to their formation process

J. Blum [a], B. Gundlach [a,*], S. Mühle [a], J.M. Trigo-Rodriguez [b]

[a] *Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Mendelssohnstr. 3, D-38106 Braunschweig, Germany*
[b] *Institute of Space Sciences (CSIC), Campus UAB, Facultat de Ciéncies, Torre C-5 pares, 2a pl., 08193 Bellaterra (Barcelona), Spain*

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ABSTRACT

When comet nuclei approach the Sun, the increasing energy flux through the surface layers leads to sublimation of the underlying ices and subsequent outgassing that promotes the observed emission of gas and dust. While the release of gas can be straightforwardly understood by solving the heat-transport equation and taking into account the finite permeability of the ice-free dust layer close to the surface of the comet nucleus, the ejection of dust additionally requires that the forces binding the dust particles to the comet nucleus must be overcome by the forces caused by the sublimation process. This relates to the question of how large the tensile strength of the overlying dust layer is. Homogeneous layers of micrometer-sized dust particles reach tensile strengths of typically 10^3 to 10^4 Pa. This exceeds by far the maximum sublimation pressure of water ice in comets. It is therefore unclear how cometary dust activity is driven.

To solve this paradox, we used the model by Skorov and Blum (Skorov, Y.V., Blum, J. 2012. Icarus 221, 361–11), who assumed that cometesimals formed by gravitational instability of a cloud of dust and ice aggregates and calculated for the corresponding structure of comet nuclei tensile strength of the dust-aggregate layers on the order of 1 Pa. Here we present evidence that the emitted cometary dust particles are indeed aggregates with the right properties to fit the model by Skorov and Blum. Then we experimentally measure the tensile strengths of layers of laboratory dust aggregates and confirm the values derived by the model. To explain the comet activity driven by the evaporation of water ice, we derive a minimum size for the dust aggregates of ~1 mm, in agreement with meteoroid observations and dust-agglomeration models in the solar nebula. Finally we conclude that cometesimals must have formed by gravitational instability, because all alternative formation models lead to higher tensile strengths of the surface layers.

1. Introduction: formation scenarios of planetesimals and cometesimals

It is now well established that dust inside the snow line of the solar nebula quickly coagulated into millimeter- to centimeter-sized agglomerates due to direct sticking in collisions (Güttler et al., 2010; Zsom et al., 2010). The further growth to planetesimal-sized objects is still under debate, with two major scenarios under consideration: the mass transfer scenario (1) and the gravitational instability scenario (2).

(1) As direct sticking is mostly prevented by bouncing among the dust aggregates (Blum and Münch, 1993; Langkowski et al., 2008; Weidling et al., 2009, 2012; Beitz et al., 2012; Schräpler et al., 2012; Deckers and Teiser, 2013), only those particles colliding with velocities slower than the sticking-bouncing transition can further grow, whereas the fastest collisions in the ensemble lead to fragmentation with mass transfer (Windmark et al., 2012a,b; Garaud et al., 2013). This latter process has been extensively studied in the laboratory (Wurm et al., 2005; Teiser and Wurm, 2009b,a; Güttler et al., 2010; Kothe et al., 2010; Teiser et al., 2011) and is now well established for aggregates consisting of micrometer-sized silicate grains. It has been shown that in principle planetesimals can form by this process (Windmark et al., 2012a,b; Garaud et al., 2013) although the timescales are rather long and details about counteracting processes (e.g., erosion; Schräpler and Blum, 2011) need to be clarified.

(2) Alternatively, Johansen et al. (2007) showed that cm-sized particles can be sufficiently concentrated by the streaming

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[*] Corresponding author.
E-mail address: b.gundlach@tu-bs.de (B. Gundlach).

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instability (Youdin and Goodman, 2005) so that the ensemble becomes gravitationally unstable and forms planetesimals. Also here, several details need to be clarified before this process can be regarded as established, e.g. the collisional fate of the dust agglomerates within the instabilities, fragmentation of the collapsing cloud and the mass distribution function of the resulting planetesimals, and the required high metallicity of the solar nebula.

In the outer solar nebula beyond the snow line, the dominant material should be (water) ice. Due to the higher anticipated stickiness of water–ice particles (Gundlach et al., 2011a), ice aggregates are supposed to grow to larger masses and fluffier structures in the outer solar nebula (Wada et al., 2008, 2009; Okuzumi et al., 2012; Kataoka et al., 2013). As empirical proof for this concept from laboratory experiments is still missing, it can only be speculated whether icy planetesimals form directly by hit-and-stick collisions, or by a multi-step process. If direct formation of cometesimals is not feasible, similar processes as discussed above for the inner solar nebula might also apply for its outer reaches.

Since the first space missions to Comet Halley it has been known that comets consist in almost equal parts of ice and refractory materials (dust), with the addition of organic materials (Jessberger et al., 1988), which in turn led to revised cometary dust modeling (Greenberg and Hage, 1990; Li and Greenberg, 1997; Greenberg, 1998). The samples brought back from Comet 81P/Wild by the Stardust mission revealed that the refractory materials are high-temperature condensates, which must have been radially mixed outwards before the formation of the comet nucleus (McKeegan, 2006; Zolensky et al., 2006). As the growth timescales to mm or cm sizes are rather short in the inner solar nebula (a few 10^3 years) and as the dust aggregates are supposed to be rather compact (with a porosity of "only" 60—65%, according to Zsom et al. (2010) and Weidling et al. (2009)), with any further growth slowed down due to the decreased stickiness of large dust aggregates (Güttler et al., 2010), it is plausible to assume that the refractory materials were mixed into the outer solar nebula in form of mm- to cm-sized agglomerates (see also Sections 2 and 3). Hence, cometesimals in the outer solar nebula were then formed out of icy and dusty agglomerates by one of the two processes described above, namely (1) fragmentation with mass transfer (MT) or (2) spatial enhancements in (magneto-) hydrodynamic instabilities with subsequent gravitational instability (GI). From this line of reasoning, we can derive several physical distinctions in the resulting icy–dusty planetesimals. We summarize these in the Table 1. It should be mentioned that we assume that the formation process for cometesimals was the same anywhere in the outer solar nebula. Thus, the following discussion in this paper refers to both, Kuiper-belt and Oort-cloud comets. As to the formation timescales for cometesimals, these are required to be long enough for the radial mixing of the high-temperature condensates to occur, but certainly shorter that the lifetime of the nebula gas. As this might be a problem for the MT origin of cometesimals at large heliocentric distances, the timescales for the instability-driven formation of cometesimals should always be sufficiently short. In the latter, however, the aggregate sizes at which the bouncing barrier is reached and for which then some concentration process forms a gravitationally unstable cloud, could be considerably different (albeit yet unknown) for the two reservoirs of Kuiper-belt and Oort-cloud comets.

Table 1
Comparison between the two formation scenarios of icy–dusty planetesimals. GI stands for gravitational instability, MT represents the process of mass transfer.

	GI		MT	
Volume filling factor	$0.35 \times 0.6 \approx 0.2$	[1,7]	$\sim$0.4	[2]
Tensile strength of interior (Pa)	$\sim$10	[3]	$\sim$10,000	[2,5]
Tensile strength of ice-free outer dust layer (Pa)	$\sim$1	[3]	$\sim$1000	[2,5]
Gas permeability ($m^4\ s^{-1}$)	$\sim 1 \times 10^{-6}$	[4]	$\sim 1 \times 10^{-9}$	[4]
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	10^{-3}–1 (conduction/ radiation)	[6]	10^{-2}–10^{-1} (conduction)	[6]

References:
[1] Weidling et al. (2009), [2] Kothe et al. (2010), [3] Skorov and Blum (2012), [4] Gundlach et al. (2011b), [5] Blum et al. (2006), [6] Gundlach and Blum (2012), [7] Zsom et al. (2010).

The volume filling factor ϕ is defined as the fraction of the total volume occupied by the material and is related to the porosity ψ by $\phi = 1 - \psi$. For an icy–dusty planetesimal formed by the GI process, the volume filling factor is determined by the packing fraction of the dust aggregates into the planetesimal ($\phi_{\text{global}} \approx 0.6$, if we assume that the dust aggregates pack almost as densely as possible) and by the volume filling factor of the individual dust aggregates ($\phi_{\text{local}} \approx 0.35$, according to Weidling et al. (2009)). The volume filling factor of the MT dust aggregates has been measured to be close to $\phi_{\text{local}} = 0.4$ (Kothe et al., 2010). The tensile strength of a package of dust aggregates, which collapsed under their own gravity to form a km-sized body with a volume filling factor of ϕ_{global} has been calculated by Skorov and Blum (2012) to be

$$p_{\text{tensile}} = p'_{\text{tensile}}\,\phi_{\text{global}}\left(\frac{s}{1\ \text{mm}}\right)^{-2/3}, \qquad (1)$$

with $p'_{\text{tensile}} = 1.6$ Pa and s being the radius of the infalling dust aggregates. For ice aggregates, the tensile strength is supposed to be a factor of ten higher (Gundlach et al., 2011a). In the case of planetesimals formed by the MT process, their rather compact packing of the monomer grains ensures a relatively higher tensile strength of $\sim$1 kPa for volatile-free and $\sim$10 kPa for icy particles (Blum et al., 2006). Due to the smaller pore size in the planetesimals formed by MT (the pore size is on the order of the monomer-grain size, i.e., $\sim$1 μm, whereas for planetesimals formed by GI the pore size is on the order of the aggregate size), the gas permeability is much lower (Gundlach et al., 2011b). The thermal conductivity is not easily distinguishable between the two formation models, due to the fact that for large pore sizes, radiative energy transport is no longer negligible (Gundlach and Blum, 2012). Thus, the range of possible thermal-conductivity values is much larger for the GI-formed planetesimals than for those formed by MT.

As mentioned above, Skorov and Blum (2012) were the first to bring up the distinction in tensile strength between the two models, who related the formation of icy–dusty planetesimals to present comet nuclei, and who showed that, according to their model (see Eq. (1)), only the GI model can explain a continued gas and dust activity of a comet. Their model for the tensile strength of the ice-free outer layers of a comet nucleus is based on the assumption that dust and ice aggregates once formed the comet nucleus by gravitational instability so that essentially the aggregates collapsed below or at the very low escape speed of the kilometer-sized body. Thus, the aggregates are only slightly deformed and the resulting binding between the clumps is much weaker than in the mass-transfer process.

In this article, we intend to verify the model by Skorov and Blum (2012) and to support their statement that comets were formed in gravitational instabilities. This will be done in the following: in Section 2 we will show that comet nuclei indeed consist of mm- to cm-sized dust particles and ice clumps with at least these sizes. In Section 3, we will then show that observed cometary dust aggregates or meteoroids are consistent with model expectations for dust aggregates in the bouncing regime, i.e. with a rather low porosity and a correspondingly rather low tensile strength p_{tensile} (in this paper, we denote $p_{\text{tensile}} \sim 1$ kPa as low tensile