PEBBLES

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Pebbles (if any) must be made of (icy) dust particles

Dust classification after IDPs, Rosetta, Stardust (Güttler et al. 2019 AA 630, A24)

<table>
<thead>
<tr>
<th>solid group</th>
<th>fluffy group</th>
<th>porous group</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLID_1: irregular grain</td>
<td>FLUFFY_1: fractal, dendritic agglomerate (with $m \propto r^{D_f}$ and $D_f$ typically 1.5 .. 2.5)</td>
<td>POROUS_1: porous agglomerate</td>
</tr>
<tr>
<td>roundish monomer (e.g., in computer models)</td>
<td>$&lt; 1$ cm</td>
<td>&quot;average&quot; dust particle $&lt; 1$ cm</td>
</tr>
<tr>
<td>SOLID_2: dense aggregate of grains</td>
<td></td>
<td>&quot;pebble&quot; $\sim 1$ cm</td>
</tr>
<tr>
<td>$&lt; 1$ mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
From classification to samples

Fig. 9: Rosetta/MIDAS AFM image at best resolution: grains (monomers) of a size peak at 100 nm

Fig. 5: Bigger aggregates of grains, typical volume filling factor = 0.6 (v.f.f. = 1 – porosity)

Fig. 6: Rosetta/MIDAS and Rosetta/COSIMA images, sizes from few micron to sub-mm

Lower left: most particles are mixtures of rocks and porous aggregates, Stardust sample:
[SOLID_2 = sulfide (lower right) + silicate (middle)] + [POROUS] (Güttler et al 2019 AA 630, A24)
Fluffy particles require pebbles to survive

Fractal particles cannot form on comets: heritage of the first dust accretion in the presolar cloud. Both MIDAS and GIADA infer a fractal dimension ~1.7, consistent with primordial growth.

Fractal dust of size <1 cm requires storage in voids among much more robust cm-sized pebbles. Comets did not undergo catastrophic collisions completely reshuffling the structure of nuclei.

Fulie & Blum 2017 MNRAS 469, S39

Fig. 4. Fractal particles from laboratory experiments (left), computer simulation (top right), and Rosetta/MIDAS (bottom right, left and right of the scale bar; references in the text). The color code and scale bar for the bottom right image denotes height.
## Evolution from Grains to Pebbles to Planetesimals

<table>
<thead>
<tr>
<th>Dominant Process</th>
<th>Evolutionary Step</th>
<th>v.f.f.</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presolar grain</td>
<td>Presolar grain</td>
<td>~1</td>
<td>~100nm</td>
</tr>
<tr>
<td>Sticking</td>
<td>Grains $\rightarrow$ Fractal particles</td>
<td>&lt;0.01</td>
<td>&lt;1 cm</td>
</tr>
<tr>
<td>Sticking + bouncing</td>
<td>Fractals $\rightarrow$ Porous particle</td>
<td>~0.4</td>
<td>~1 mm</td>
</tr>
<tr>
<td>Disc mixing + sticking</td>
<td>Porous $\rightarrow$ Rocks+Porous</td>
<td>~0.6</td>
<td>~1 cm</td>
</tr>
<tr>
<td>Erosion barrier</td>
<td>Particles $\rightarrow$ Pebbles + fractals</td>
<td>~0.4</td>
<td>~1 cm</td>
</tr>
<tr>
<td>Disc instability + gravity</td>
<td>Pebbles $\rightarrow$ Planetesimals</td>
<td>~0.25 - 1</td>
<td>1-1000km</td>
</tr>
</tbody>
</table>

If the planetesimal size <100 km, then pebbles are not destroyed by self-gravity and radio decays (in which case v.f.f. ~ 1) $\rightarrow$ COMETS of v.f.f. ~ 0.25
Erosion barrier: no growth above ~10 cm

Left: Dust collision experiments (lab. and low gravity) + models (Blum 2018, SSR 214,52)
Lower right: ice does not help, its larger sticking has no effects (Lorek et al. 2018, AA 611, A18)
Protoplanetary discs are made of pebbles

Tazzari et al. 2016, AA 588, A53
Streaming Instability most efficient at $\sim 1$ cm

Yang et al. 2017, AA 606, A80
Are comets made of pebbles?
Philae/CIVA direct observation of cm-sized pebbles

Thermal model of 67P pebble-made nucleus

Fit of orbiter (MIRO) and lander (MUPUS) thermal data (Blum et al. 2017, MNRAS 469, S755)
67P nucleus tomography finds a pebble-made nucleus

Rosetta/CONSERT data (red line) are only consistent with porosity heterogeneities at lengths <1m; at larger scales, porosity changes <10%; refractory-to-ice ratio >3 (Herique et al. 2019, AA 630, A6)
Green lines: bulk density range (RSI); Blue lines: refractory-to-ice mass ratio = 2 (left) and 6 (right)
Gas diffusion inside a dust-made pebble

The dust size spectrum constrains that of pores → Knudsen diffusivity (Fulle et al. 2019, ApJ 879, L8)
If pebbles >10 cm, then diffusion time scale >0.5hr: never observed any such activity delay at sunrise
Gas diffusion model from ice sublimation inside dust fits all 67P activity data (Fulle et al. 2020, subm.)
The pebble model fixes the refractory-to-ice ratio

Pebble-made comets must have refractory-to-ice > 3 (Lorek et al. 2019, AA 587, A128)
All cometary data confirm refractory-to-ice ratio > 3 (Fulle et al. 2019, MNRAS 482, 3326)
Conclusions

..........up to now, pebbles only explain “everything”..........