The Aeolian-Erosion Barrier for The Growth of Metre-Size Objects in Protoplanetary-Discs

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Erosion is a very common destructive process

(a) Wind erosion

(b) Water erosion
There are three types of aeolian erosion:

1. **Wind**: Sand is picked up by the wind and carried away.
2. **Suspension**: Sand is lifted into the air by turbulence and lifted by jet streams.
3. **Saltation**: Sand is carried across the ground by the wind, bouncing along the surface.
4. **Creep**: Sand is transported by gravity and surface flow, moving slowly over the ground.
Suspension takes place in protoplanetary-discs

- Aeolian-erosion is purely mechanical – no need for high temperatures 
  this is not a thermal ablation – gas-drag is the 'wind'
- The lifted particles are small – suspension fits better than saltation or creep
- Self-gravity is negligible below $\sim 1\text{km}$, cohesion force plays its role

Suspension in the lab, Paraskov et al. 2006
Suspension requires a threshold velocity

- The 'wind' – drag-force – should be strong enough in order to overpower the cohesion.
- Drag-force $F_D = \frac{1}{2} \rho g C_D \pi R^2 v_{rel}^2$ vs. cohesion $F_c = \beta d$ per particle
- Shao & Lu 2000 (without self-gravity):

$$v_* = \sqrt{\frac{A_N \gamma}{\rho g d}}$$
The threshold velocity depends on the size of the grain and the gas density.
Above the threshold, the erosion rate can be prescribed analytically.

The shear pressure induces a mass loss in rate, similarly to Bagnold’s model from 1941:

\[
\frac{dR}{dt} = - \frac{\rho_g v_{rel}^3}{4\pi R \rho_p a_{cohesion}}
\]

- \(\rho_g\) - gas density
- \(v_{rel} = \sqrt{v_{rel,\phi}^2 + v_{rel,r}^2}\) - velocity relative to the gas
- \(R\) - radius of the object
- \(\rho_p\) - density of the object
- \(a_{cohesion}\) - the acceleration due to cohesion force
Aeolian-erosion is very efficient

\[
\begin{align*}
R_0 & = 100.0 \text{cm} \\
R_0 & = 500.0 \text{cm} \\
R_0 & = 1000.0 \text{cm} \\
R_0 & = 2000.0 \text{cm} \\
R_0 & = 5000.0 \text{cm}
\end{align*}
\]
Aeolian-erosion gets stronger when we get closer.
Aeolian-erosion enriches the abundance of small objects in the disc

- Aeolian-erosion dictates a final-size which depends on the distance from the centre of the disc
- The final-size is about $\sim 10\text{cm}$ (depends on the object and disc parameters)
- Aeolian-erosion creates an abundance of small pebbles, which strengthen pebble-accretion of large objects – once they are formed (somehow...)
Shape could play a role

- Here we assumed a spherical shape during the whole process
- Generally, aeolian-erosion could reshape objects and explain the formation of objects like 'Oumuamua
Radial-drift isn’t that strong anymore

Dashed lines include radial-drift
Summary

- Aeolian-erosion sets a new barrier in planet formation
- In order to start the aeolian-erosion, the object should move faster than a threshold velocity
- Above the threshold velocity, aeolian-erosion is very efficient
- Aseloian-erosion assists growth of larger objects via pebble-accretion
Backup Slides
The gas in the disk could be turbulent

- Turbulence adds random-kicks to the velocity of objects in the disk
  \[ \langle \delta v^2 \rangle = \langle \delta v_{\text{rel}}^2 \rangle + \langle v_{\text{turb}}^2 \rangle \]

- Ormel & Cuzzi 2007 – and references therein traces back to Völk 1980 – gave expressions for the relative velocities between object in turbulent media
  \[
  v_{pg,t} = v_t S_t \sqrt{\frac{1 - Re_t^{-1/2}}{(S_t + 1)(S_t + Re_t^{-1/2})}}
  \]
  (1)
Kicks from turbulence enhance aeloian-erosion

\[ R(t) \] vs. \[ \text{time [Myr]} \]

- \( R_0 = 100.0 \text{cm} \)
- \( R_0 = 500.0 \text{cm} \)
- \( R_0 = 1000.0 \text{cm} \)
- \( R_0 = 2000.0 \text{cm} \)
- \( R_0 = 5000.0 \text{cm} \)
Cohesion (see Shao&Lu 2000)

\[ F_{\text{cohesion}} = \beta d, \quad \beta \approx 10^2 \frac{cm \cdot g}{sec} \quad (2) \]

where \( \beta \) engulfs parameters that arise from Van-der-Waals interaction and electrostatic force.

\[ \beta \propto \sqrt{\frac{A_N \gamma}{\rho g}} \quad (3) \]

We used

\[ \gamma = 0.165 \frac{g}{\sec^2}, \quad A_N = 0.0123 \quad (4) \]
Dependence on material

- Rock
- Porous-ice
- Metal
Dependence on temperature

![Graph](image)

- $T_0 = 100.0K$
- $T_0 = 120.0K$
- $T_0 = 150.0K$
- $T_0 = 200.0K$
- $T_0 = 250.0K$
Dependence on gas-density

The graph shows the relationship between gas density and time. The x-axis represents time in Myr (Myr = million years), and the y-axis represents distance in meters (cm). Different colors and line styles represent different initial gas densities, with specific values given in the legend:

- $\rho_g,0 = 7 \times 10^{-10} g/cm^3$ (light blue)
- $\rho_g,0 = 1 \times 10^{-9} g/cm^3$ (orange)
- $\rho_g,0 = 3 \times 10^{-9} g/cm^3$ (green)
- $\rho_g,0 = 7 \times 10^{-9} g/cm^3$ (red)
- $\rho_g,0 = 1 \times 10^{-8} g/cm^3$ (purple)

As time increases, the distance decreases, indicating a decrease in gas density with time.
Dependence on $\eta$

![Graph showing the dependence of R on time for different values of $\eta_0$.]