Electric charging of dust aggregates and its effect on dust coagulation in protoplanetary disks

Ref. : S. Okuzumi, arXiv:0901.2886

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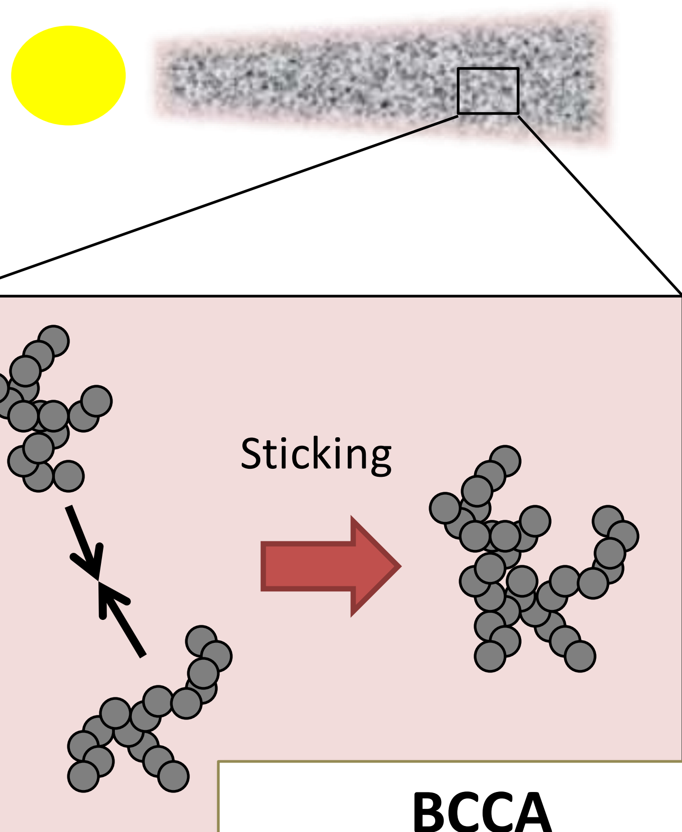
Mutual sticking of dust aggregates: the first step toward planetesimal formation



BCCA
(Ballistic Cluster-Cluster Aggregation)

Growth of small (<<km) dust aggregates

✕ Gravitational accretion (too weak)

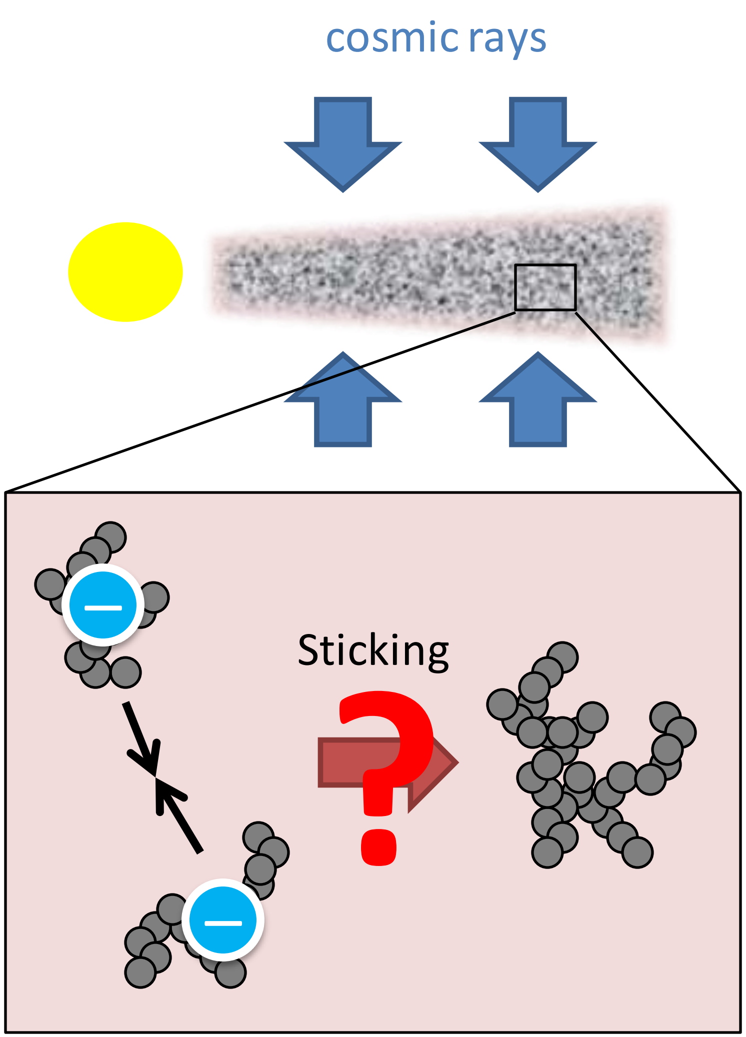
➔ Sticking by van der Waals force

Experiment (e.g. Wurm & Blum 1998) :
An ensemble of dust monomers undergoes ballistic cluster-cluster aggregation (BCCA)'.

Fractal dim.: $D_f \equiv \left(\frac{d\ln a}{d\ln N}\right)^{-1} \approx 2$

Internal Density: $\bar{\rho} \propto N^{-0.5}$
(N: # of constituent monomers)

Disk Ionization ➔ Dust Charging ➔ Can Dust Grow?



- Gas disks should be weakly ionized by Galactic cosmic rays or stellar X-rays.
- Dust charges up negatively by absorbing free electrons.

➔ **Long-range repulsion force emerges between aggregates**

Question:

Can dust aggregates in protoplanetary disks overcome this electrostatic repulsion barrier?

Aim of this study

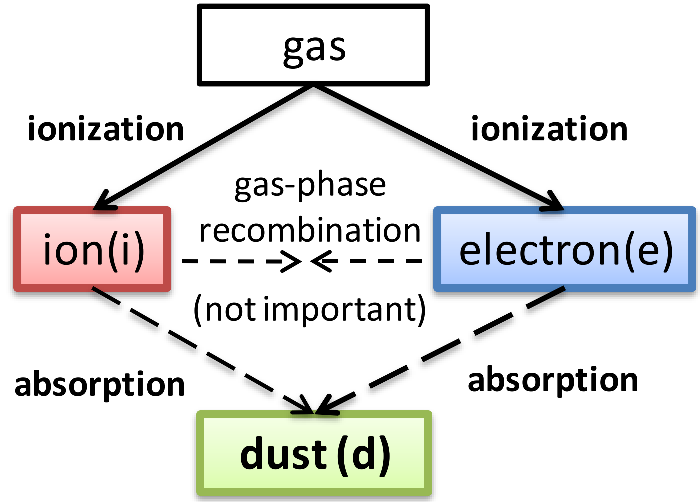
We investigate how the electric charging of dust aggregates can affect their collisional growth in protoplanetary disks.

Step 1: Formulating how to solve the dust charge state of dust aggregates in protoplanetary disks.

Step 2: Examining whether BCCA growth is inhibited by the electrostatic repulsion or not.

Equilibrium charge state of dust in weakly ionized gas

We need to solve dust charge state
and gas ionization state *self-consistently*.



Previous studies (e.g. Sano+ 2000; Ilgner & Nelson 2006)
- Numerically solve using complicated reaction schemes
- Very inefficient if we consider dust growing into large aggregates

This study: solves as analytically as possible

- ion :

$$\partial_t n_i^{(k)} = \epsilon^{(k)} \zeta n_g - n_i^{(k)} v_i^{(k)} \sum_Z \sigma_+(Z) n_d(Z) - \alpha^{(k)} n_i^{(k)} n_e - \sum_\ell \beta_{(\ell)}^{(k)} \left[n_i^{(k)} n_g^{(\ell)} - n_i^{(\ell)} n_g^{(k)} \right]$$

ionization absorption by dust recombination ion-neutral reaction

- electron :

$$\partial_t n_e = \zeta n_g - n_e v_e \sum_Z \sigma_-(Z) n_d(Z) - \sum_k \alpha^{(k)} n_i^{(k)} n_e$$

$\alpha^{(k)}$, $\beta_{(\ell)}^{(k)}$: rate coefficients

- dust :

$$\partial_t n_d(Z) = \sum_k n_i^{(k)} v_i^{(k)} [\sigma_+(Z-1) n_d(Z-1) - \sigma_+(Z) n_d(Z)] + n_e v_e [\sigma_-(Z+1) n_d(Z+1) - \sigma_-(Z) n_d(Z)]$$

$$\sigma_+(Z) = \sigma \begin{cases} \exp(-Ze^2/ak_B T) & Z \geq 0 \\ (1 - Ze^2/ak_B T) & Z < 0 \end{cases}$$

$$\sigma_-(Z) = \sigma \begin{cases} (1 + Ze^2/ak_B T) & Z \geq 0 \\ \exp(Ze^2/ak_B T) & Z < 0 \end{cases}$$

- neutrality :

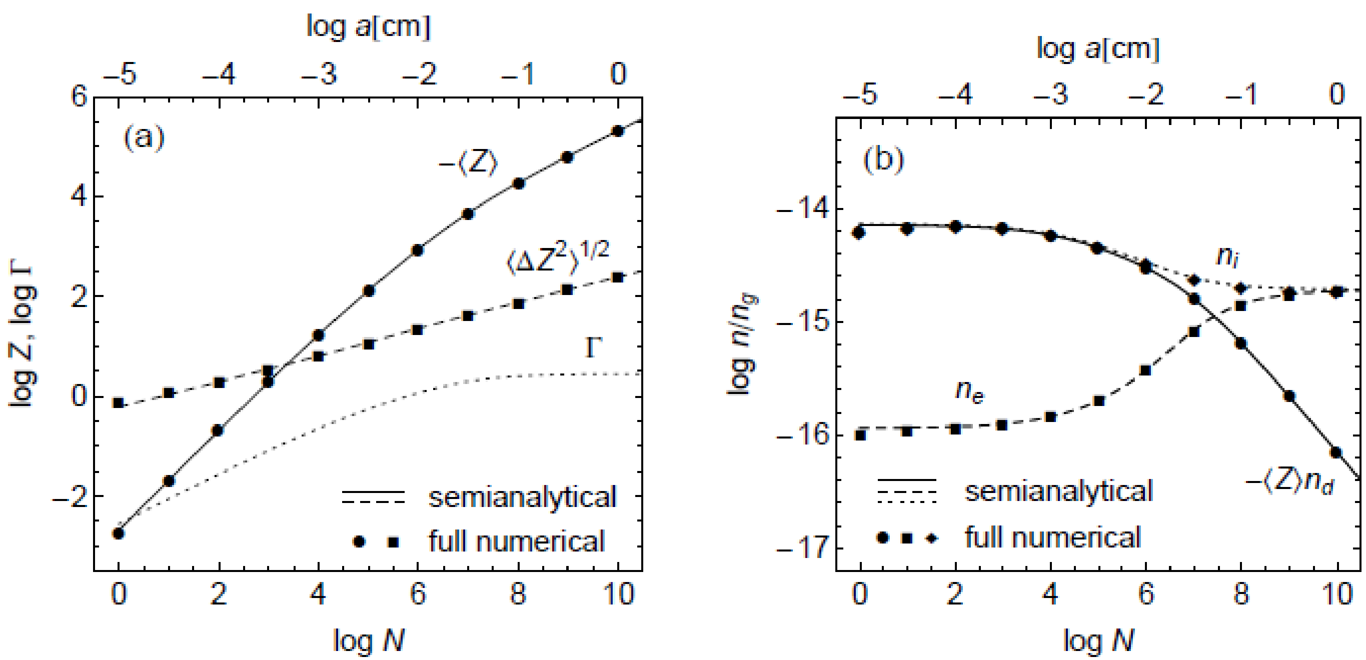
$$\sum_k n_i^{(k)} - n_e + \sum_Z Z n_d(Z) = 0$$

ζ : ionization rate
$\sim 10^{-17}$ - 10^{-22} [/s]

Semianalytical solution of dust charge state

We have found a single equation determining the self-consistent solution.
(Okuzumi, arXiv:0901.2886)

Comparison with full-numerical solutions



The aggrement between the semialalytic and full-numerical calculations is very good!!

Can dust aggregates overcome electrostatic barrier?

dust-dust collision cross section

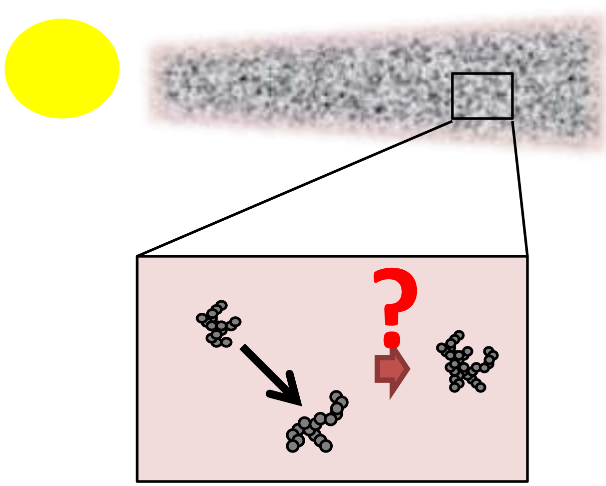
$$\sigma_{\rm eff} = \pi(a+a')^2\left(1 - \frac{E_{\rm el}}{E_{\rm kin}}\right)$$

$$\boxed{E_{\rm el} = \frac{\langle Z\rangle^2 e^2}{2a}} \quad \boxed{E_{\rm kin} = \frac{1}{2}\mu v_{\rm rel}^2}$$

Two aggregates can collide only if

$$\boxed{E_{\rm kin} > E_{\rm el}}$$

We examine whether dust aggregates can satisfy this criterion in protoplanetary disks.

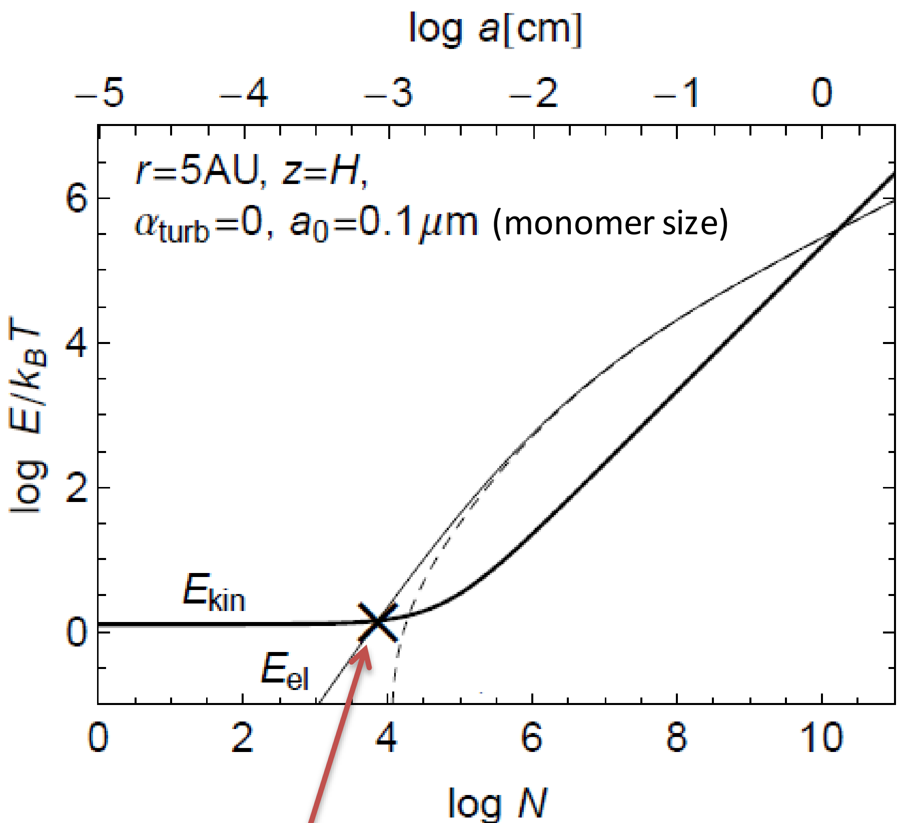


Disk model: Minimum mass solar nebula
Ionization source: Galactic cosmic rays

Dust monomer size: 0.1μm
Growth mode: Cluster-cluster aggregation (D=2)
Source of relative motion:
- Brownian motion
- Sedimentation toward midplane
- Turbulence

Kinetic energy vs electric repulsion energy

Example: r = 5 AU; z = H; no turbulence



N: number of monomers in an aggregate

a: size(radius) of the aggregate

$$a \approx a_0 N^{1/D} \qquad D \approx 2$$

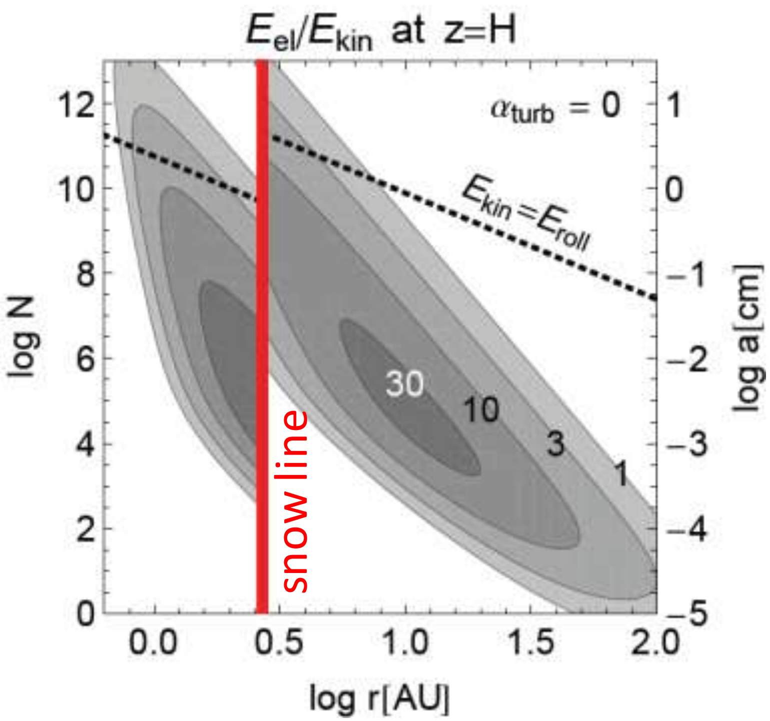
E_{kin}(thick solid curve):
kinetic energy of colliding aggregates

E_{el}(thin solid curve):
electric energy between the aggregates just before collision

At size a $\sim$ 10μm, the electric repulsion energy exceeds the kinetic energy ➔ **BCCA growth freezes out at this stage!!**

E_{kin} vs E_{el} at different disk positions (no turbulence)

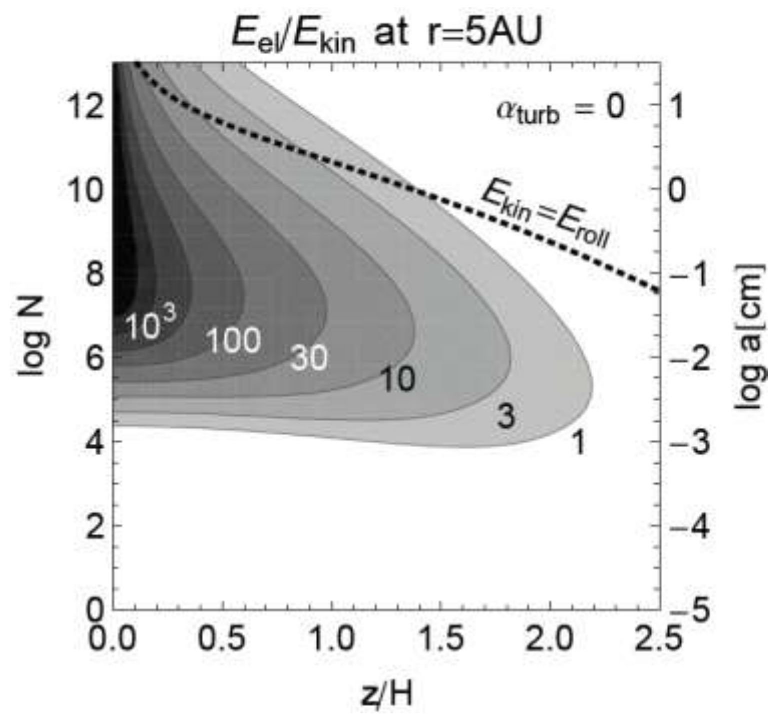
Different distances from the central star



■ For z$\lesssim$H(scale height), the growth ``barrier'' appears at r = 1AU – 100AU !!

■ The barrier is stronger inside the snow line (less solid material ➔ more free electrons ➔ more charging-up of an aggregate).

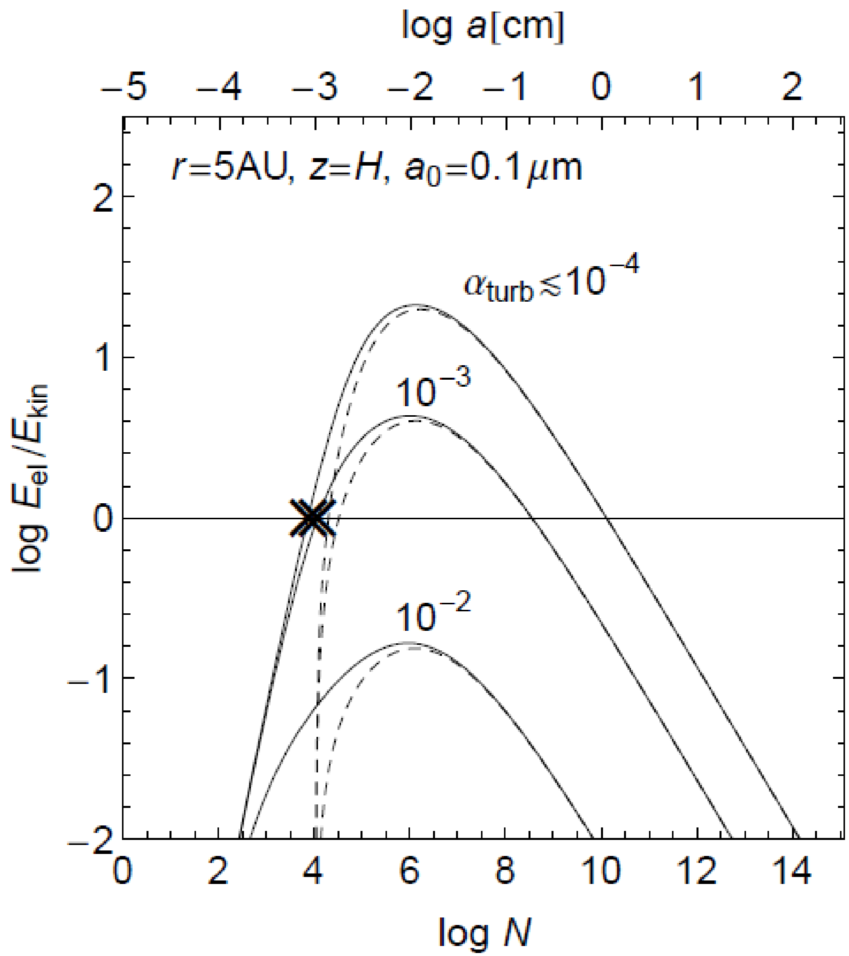
Different altitudes (distances from the midplane)



■ The growth barrier disappears only at high (z>2H) altitudes because of fast sedimentation velocity.

Effect of turbulence

Gas turbulence induces relative motion between aggregates.
➔ Does turbulence help the aggregates to overcome the electric barrier?



The left figure shows that the electric barrier disappears if the turbulence is as strong as $\alpha > 10^{-2}$

MRI-driven turbulence: $\alpha \sim 10^{-2}$
(e.g. Sano+97)

➔Dust aggregates can overcome the electric barrier in MRI-active regions.

Strong turbulence seems to be preferable to dust growth, but…

This causes another growth barrier --- collisional fragmentation of aggregates!

If $\alpha \sim 10^{-2}$, maximum collisional velocity is $\sim$ 100m/s .

On the other hand, the collisional fragmentation is catastrophic for $v > 30$m/s (Wada+08).

➔ It is very unlikely that aggregates in such strong turbulence can avoid collisional destruction!

Growth in weakly turbulent regions ← electrostatic repulsion barrier
Growth in strongly turbulent regions ← fragmentation barrier

The electric charging of aggregates, together with collisional fragmentation, may impose a very strict limitation on dust growth in protoplanetary disks.

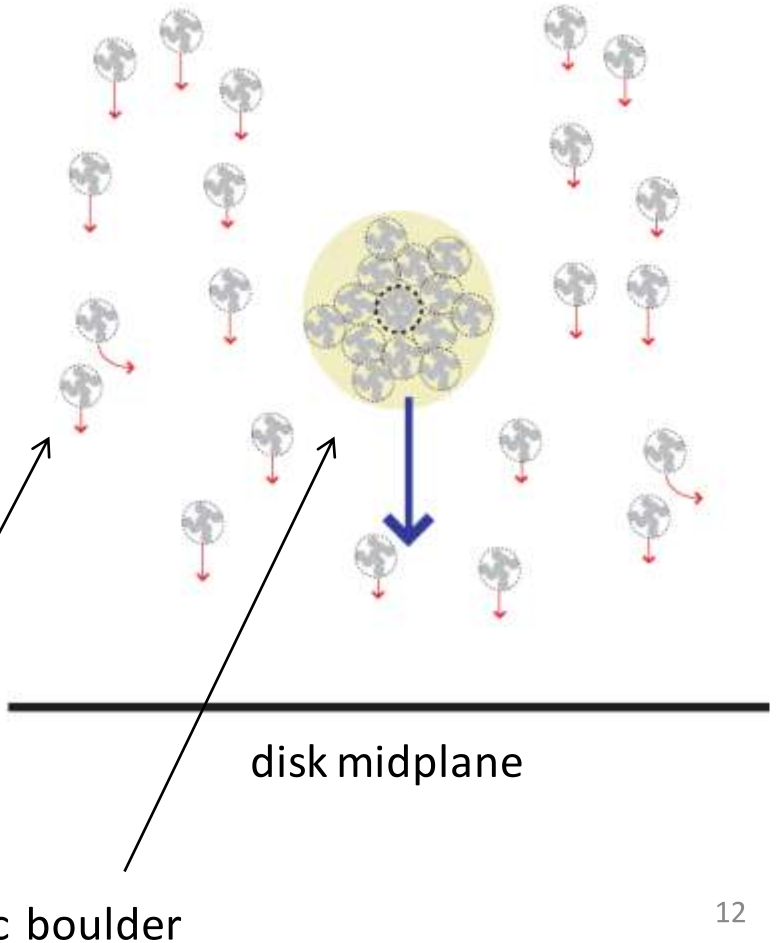
Bimodal growth hypothesis

We have seen that it is likely that BCCA growth should freeze out in its very early stage.

➔ What happens after the freeze-out ?

A simple estimation suggests that an irregularly compact (i.e. more compact than standard BCCA clusters) aggregate can collide with frozen-out aggregates.

➔We expect that the freeze-out of BCCA is followed by a ***bimodal growth*** in which only a small population of irregularly compact agrgegates continue to grow by sweeing up the large population of frozen-out BCCA clusters (see the right figure).



Summary

We have investigated the electric charge state of dust aggregates and examined the effect of the charging on dust coagulation in protoplanetary disks.

* We have discovered a semianalytic formula for dust charge state in weakly ionized gas (e.g. protoplanetary disks). This formula can be used for an arbitrary ensemble of dust aggregates, and will be easily implemented in coagulation equation solvers.

* Using the formula, we examined whether dust aggregates in protoplanetary disks can overcome the electrostatic barrier. We have found that BCCA growth is strongly inhibited by the electric repulsion and eventually freezes out.

•The combination of electric charging and collisional fragmentation may strictly limit dust coagulation in protoplanetary disks.

* The freeze-out of BCCA growth may be followed by an bimodal growth in which only a small fraction of aggregates can continue to grow.