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presents

The Role of Dust-Dust Collisional Charging in Protoplanetary Nebulae

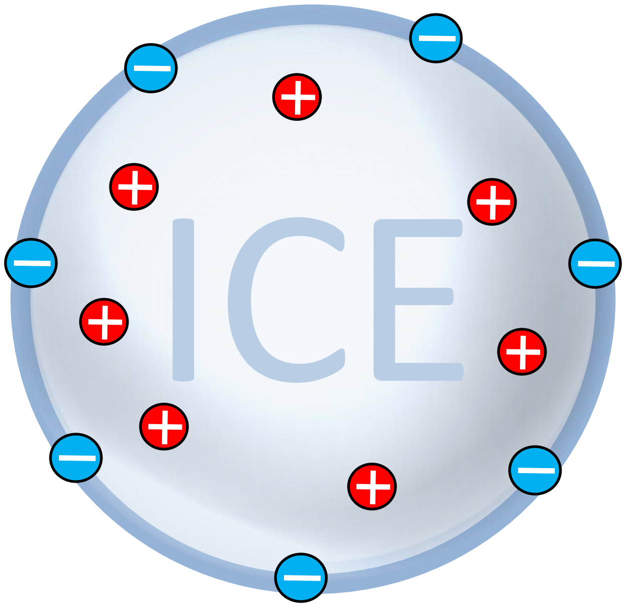
---Protoplanetary Disks Struck by Lightning?---

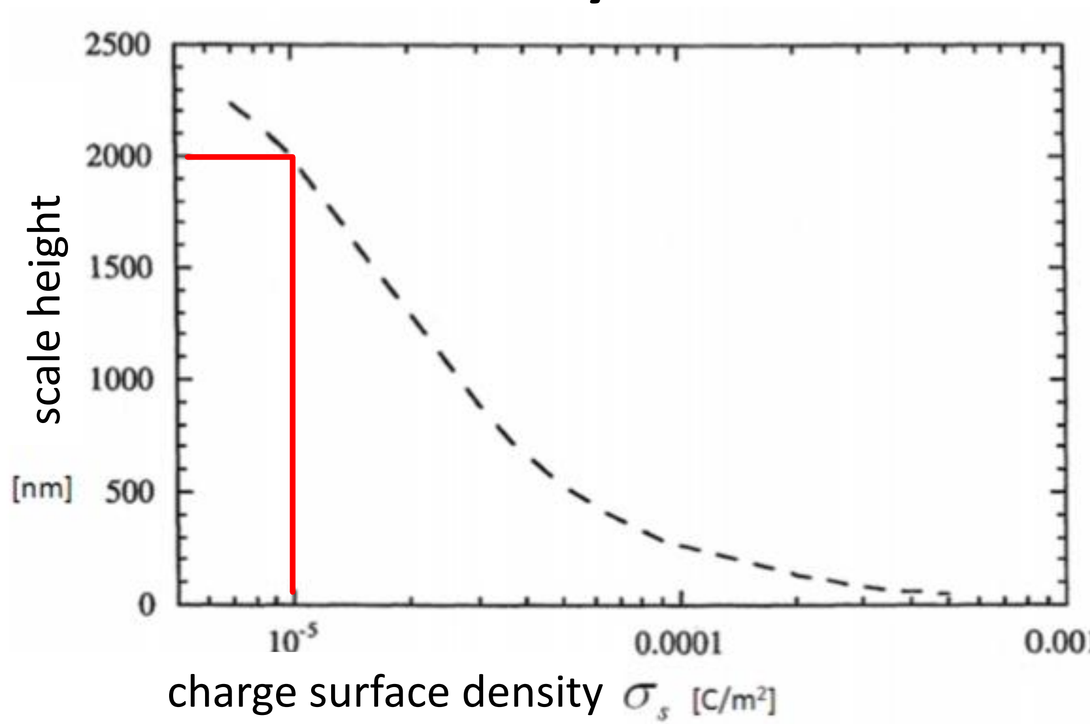
Index

Today I’m talking about collisional charging of ice dust. Profound research of the topic found in meteorology.

1. Introduction: Electric property of single ice dust, collisional charging of two ice dust, and electrical breakdown (=lightning) in terrestrial thundercloud
2. (Possible) scenario of lightning in protoplanetary disks, by analogy with 1.
3. Conditions for dust-dust collisional charging and lightning in protoplanetary disks

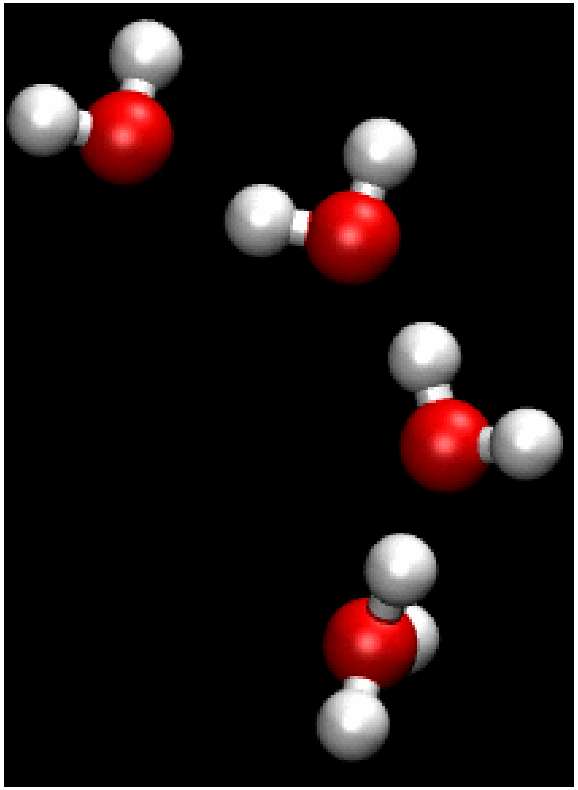
Spontaneous Charge Separation within One Water Ice Crystal

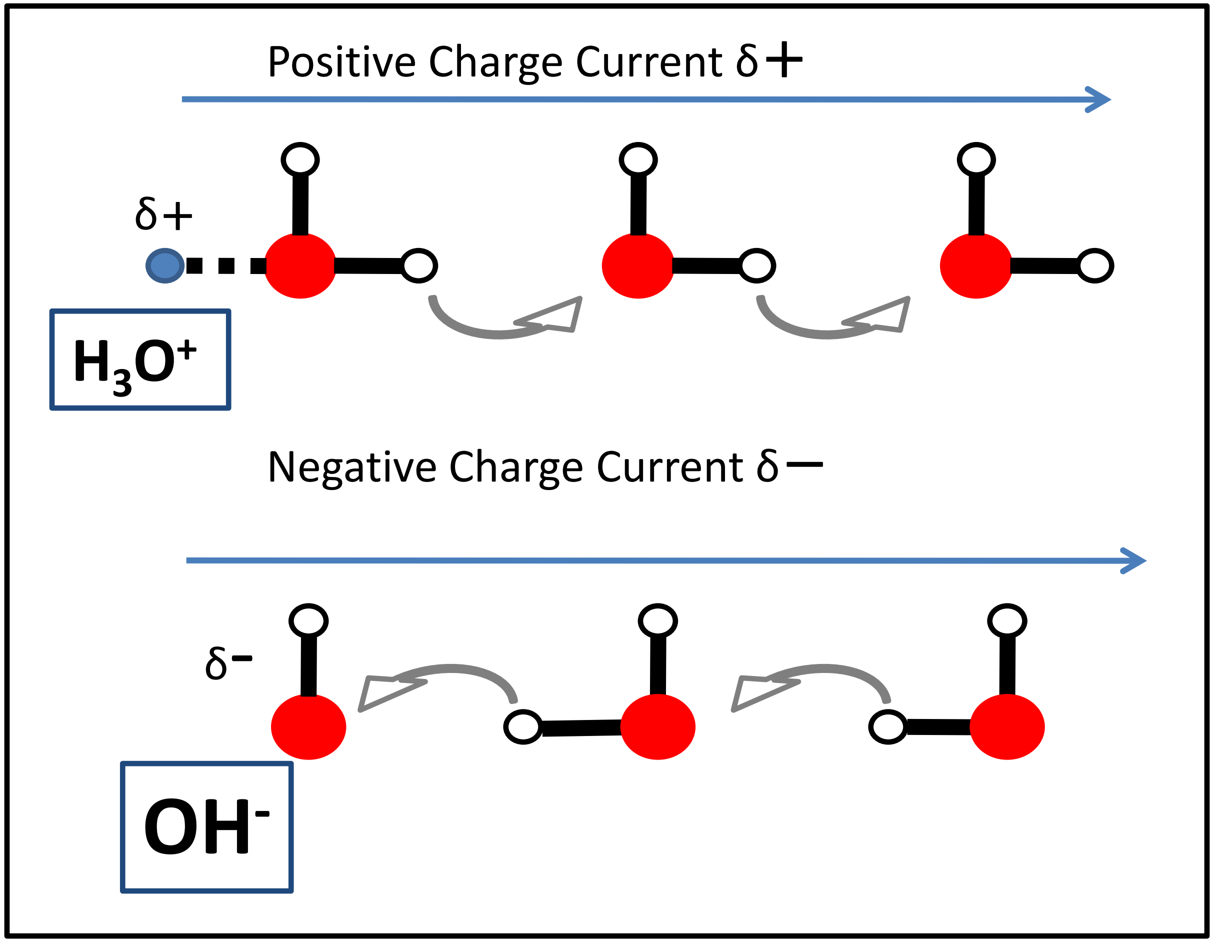




- tipical surface charge density ～ 10^{10} [e/cm^2]
- tipical charge separation depth ～ 2×10^{-4} [cm]
- but why? → (Tomiyasu Master Thesis, Tomiyasu & Muranushi, in prep)

Grotthus Mechanism – Charge Randomwalk in Ice (Grotthus, 1806)



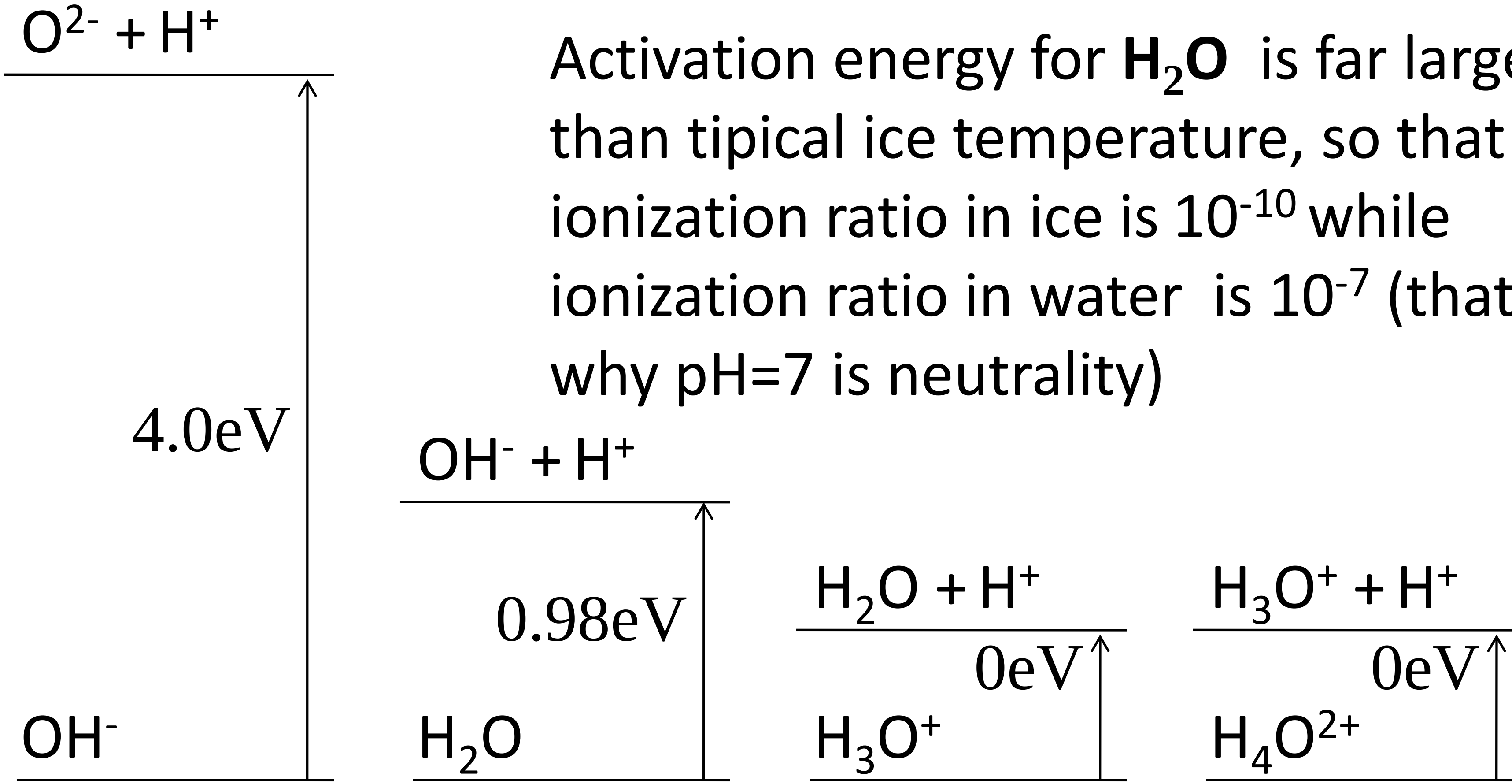


H_3O^+ and **OH^-** are main charge carrier in ice crystal. They can both move via proton exchange, or Grotthus mechanism.

How ice surface separate charge : 1/3

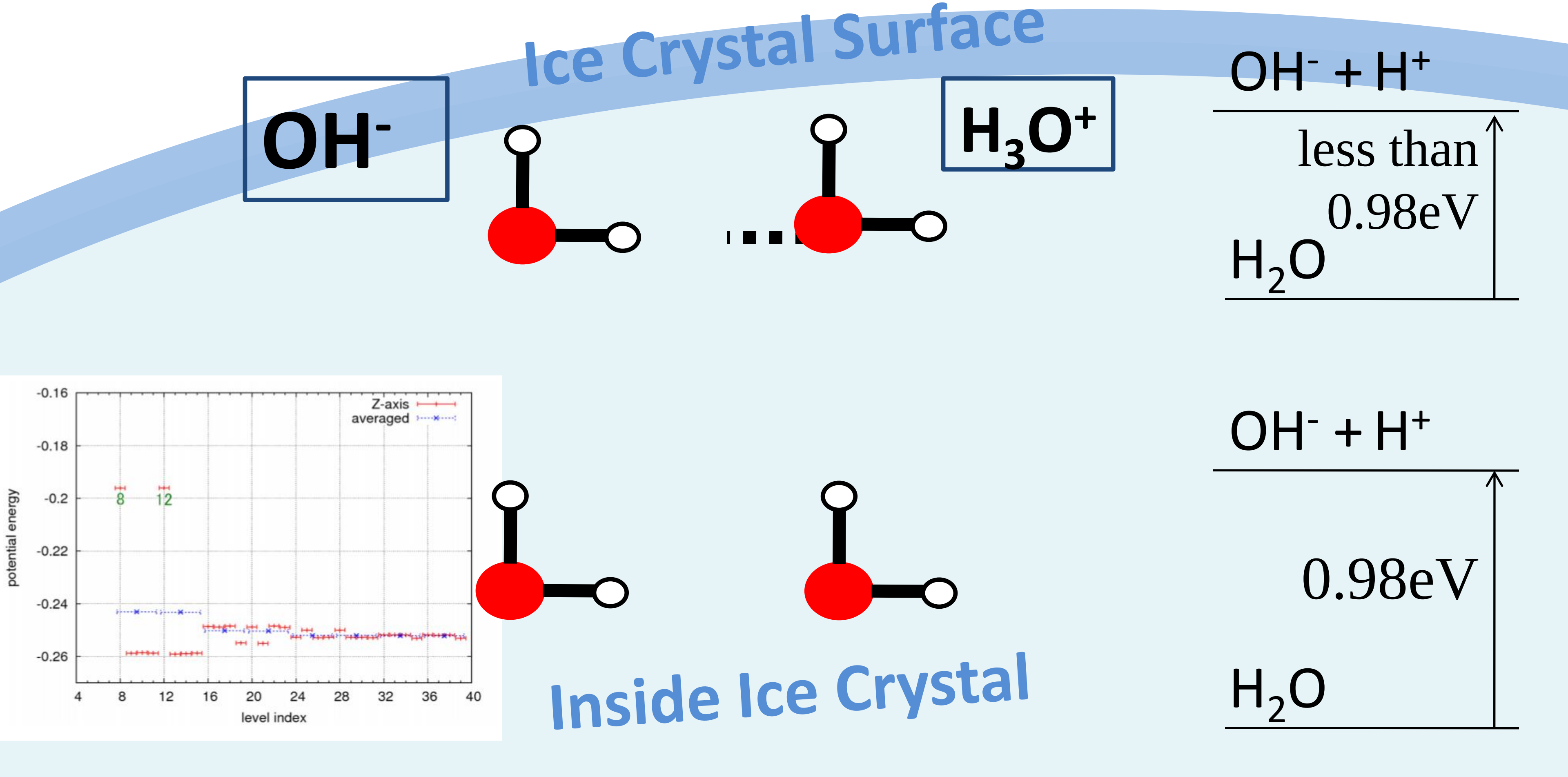
Activation energy for reaction $\mathbf{H_{\mathit{n}}O \rightarrow H_{\mathit{n}-1}O + H}$,
is smaller for larger $\boldsymbol{n}$.

Activation energy for $\mathbf{H_2O}$ is far larger than tipical ice temperature, so that ionization ratio in ice is 10^{-10} while ionization ratio in water is 10^{-7} (that's why pH=7 is neutrality)



How ice surface separate charge : 2/3

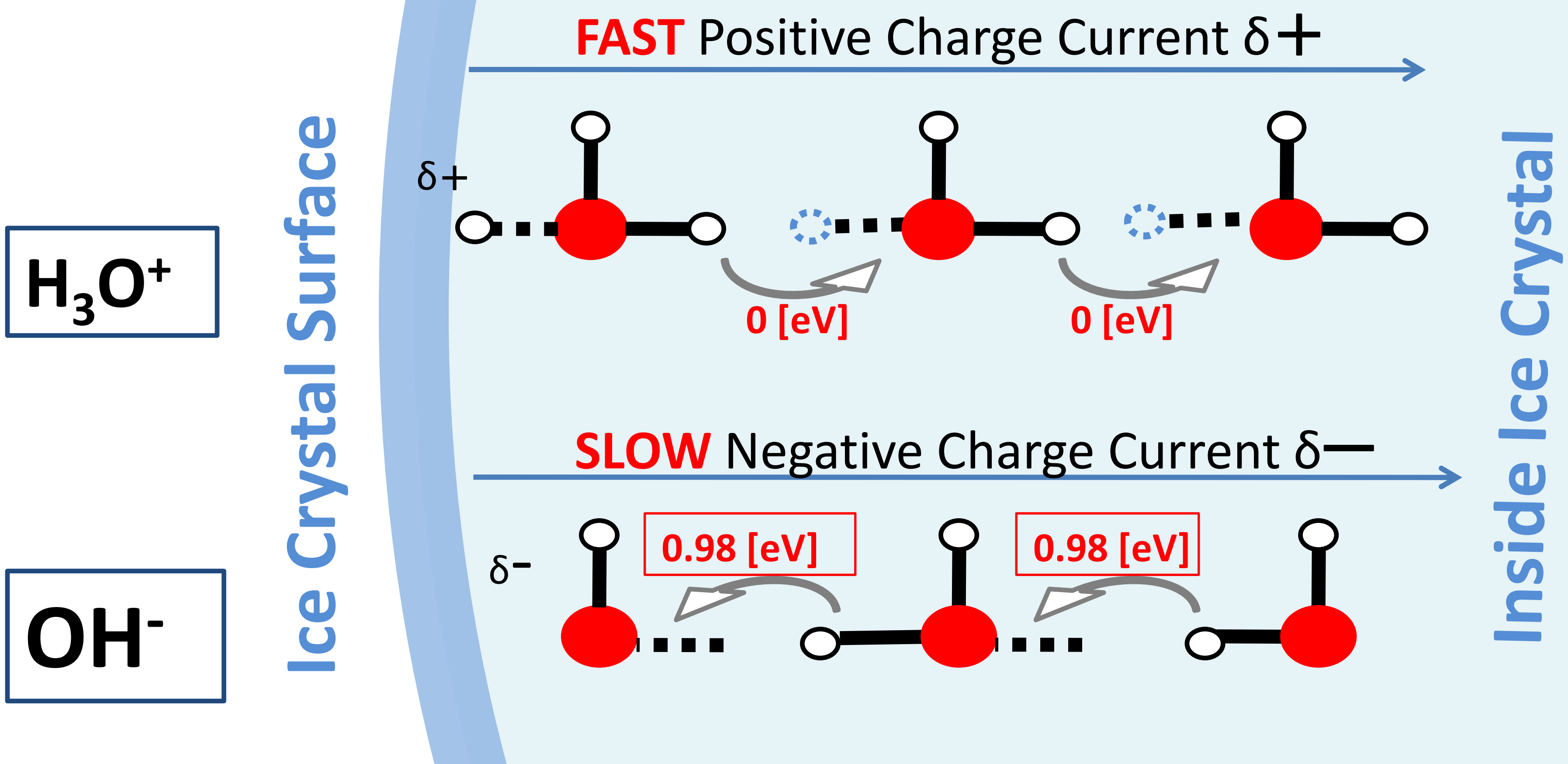
Near the crystal surface, surface tension acts to compensate the activation energy and reinforces pair creation of (H_3O^+ , OH^-)



How ice surface separate charge : 3/3

Of the two kinds of ions created at the ice surface, <u>OH^- is less mobile than H_3O^+ .</u>

- To move an **OH^-** you need to activate an **H_2O**
- To move an **H_3O^+** you need to activate an **H_3O^+**

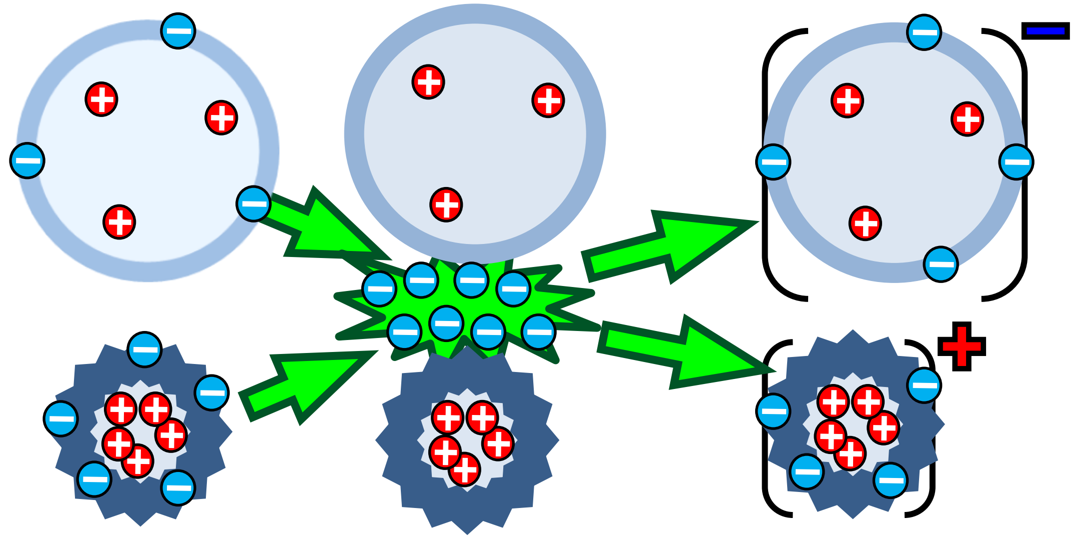


Collisional Charging of Ice Crystal

Barker et al. Meteorol. Soc., Vol.113 p.1193(1987),

Dash et al. J. Geophys. Res. Vol. 106, p 20395(2001)

- Ice has negative charge on surface and positive charge inside
- When two ice dust with different surface state collide, they exchange surface charge and each ice dust get electrically charged
- Collision between (dust made of ice) and (dust made of other material) may be more efficient in charging dust



★Electric Breakdown on Earth★

1.

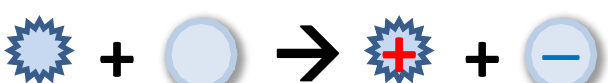
Rapid generation of small ice dust
: Dusts with Rough surface, Large Charge Separation, coupled to fluid

2.

Slow mantle accretion of large dust
: Dusts with Smooth surface, Little Charge Separation, decoupled from fluid

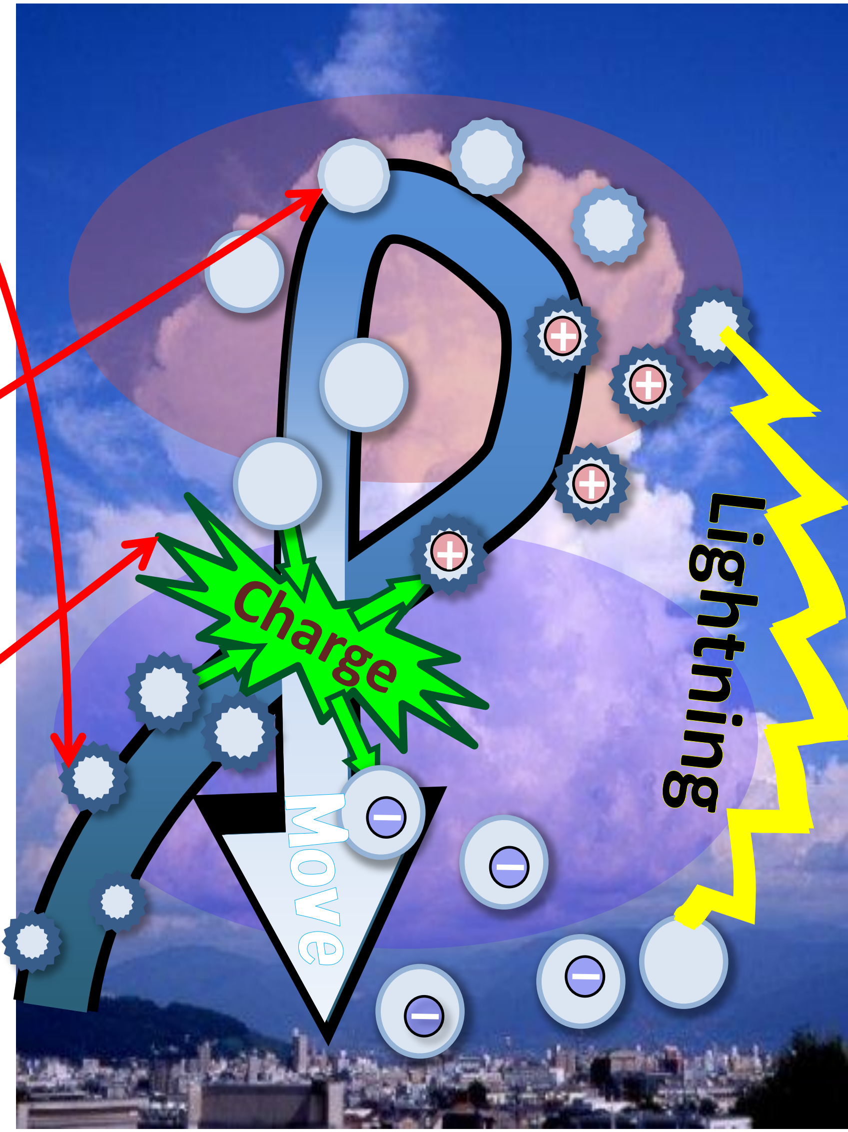
3.

Collision and Charging of Ice dust



4.

Charge Separation of ～ 50[C] ,
in height～km
(electric force ～ 1% of gravity)

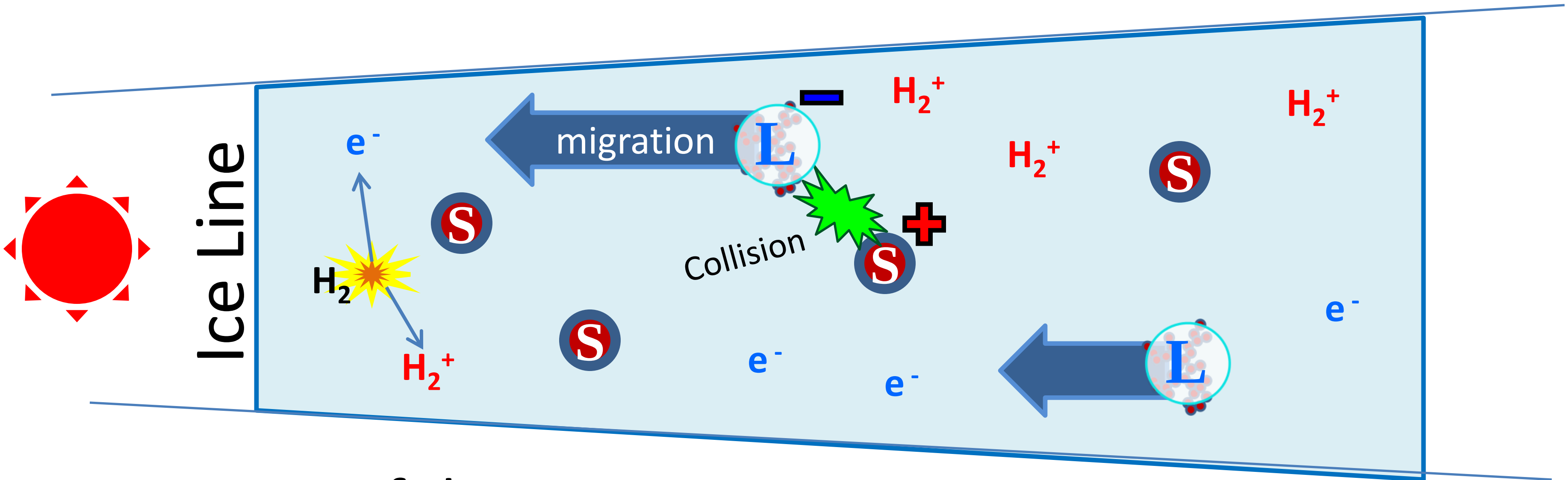


Krehbiel et al.(1983), Preceedings in Stomospheric Electricity

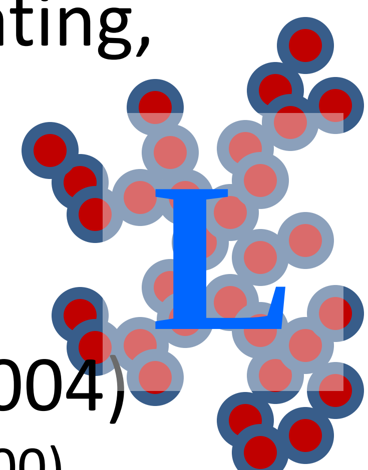
Necessary Conditions for Generating Macroscopic Electric Field

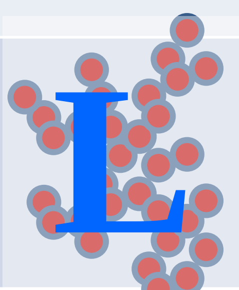
- Two group of dust with **different surface** state
- Collision between them
- **Differential mean motion** between them
- for space: Dust chargeup and electric field growth faster than **plasma neutralization** → **Dust Condensation Needed**

Lightning in protoplanetary nebulae scenario, transplanted from earth



- Two group of dust : Large aggregate migrating, small dust coupled to gas
- Collision between them
- Differential mean motion : migration
- Condensation at iceline (Cuzzi & Zahnle 2004)
- Turbulence condensation also possible(Desch & Cuzzi 2000)



Component	Unit Charge	number density	Charge density
H_2	0	n_g	0
H_2^+	+e	n_i	e n_i
e^-	-e	n_e	-e n_e
	Q_S	n_S	Q_S n_S
	Q_L	n_L	Q_L n_L

variables

Basic Equations

$$\frac{dQ_L}{dt} = -\Delta q\ n_s \sigma_{SL} \Delta v_{SL} + e\left(n_i \sigma_{iL} v_i - n_e \sigma_{eL} v_e\right)$$

Dust –Dust Collision

$$\frac{dQ_S}{dt} = +\Delta q\ n_L \sigma_{SL} \Delta v_{SL} + e\left(n_i \sigma_{iS} v_i - n_e \sigma_{eS} v_e\right)$$

Plasma Absorption

$$\frac{dn_i}{dt} = \zeta n_g - \left(n_i n_L \sigma_{iL} v_i + n_i n_S \sigma_{iS} v_i\right)$$

Ionization

$$\frac{dn_e}{dt} = \zeta n_g - \left(n_e n_L \sigma_{eL} v_e + n_e n_S \sigma_{eS} v_e\right)$$

n_L, n_S, n_i, n_e, n_g : number density for Large dust, Small dust, ion, electron, and neutral gas molecule

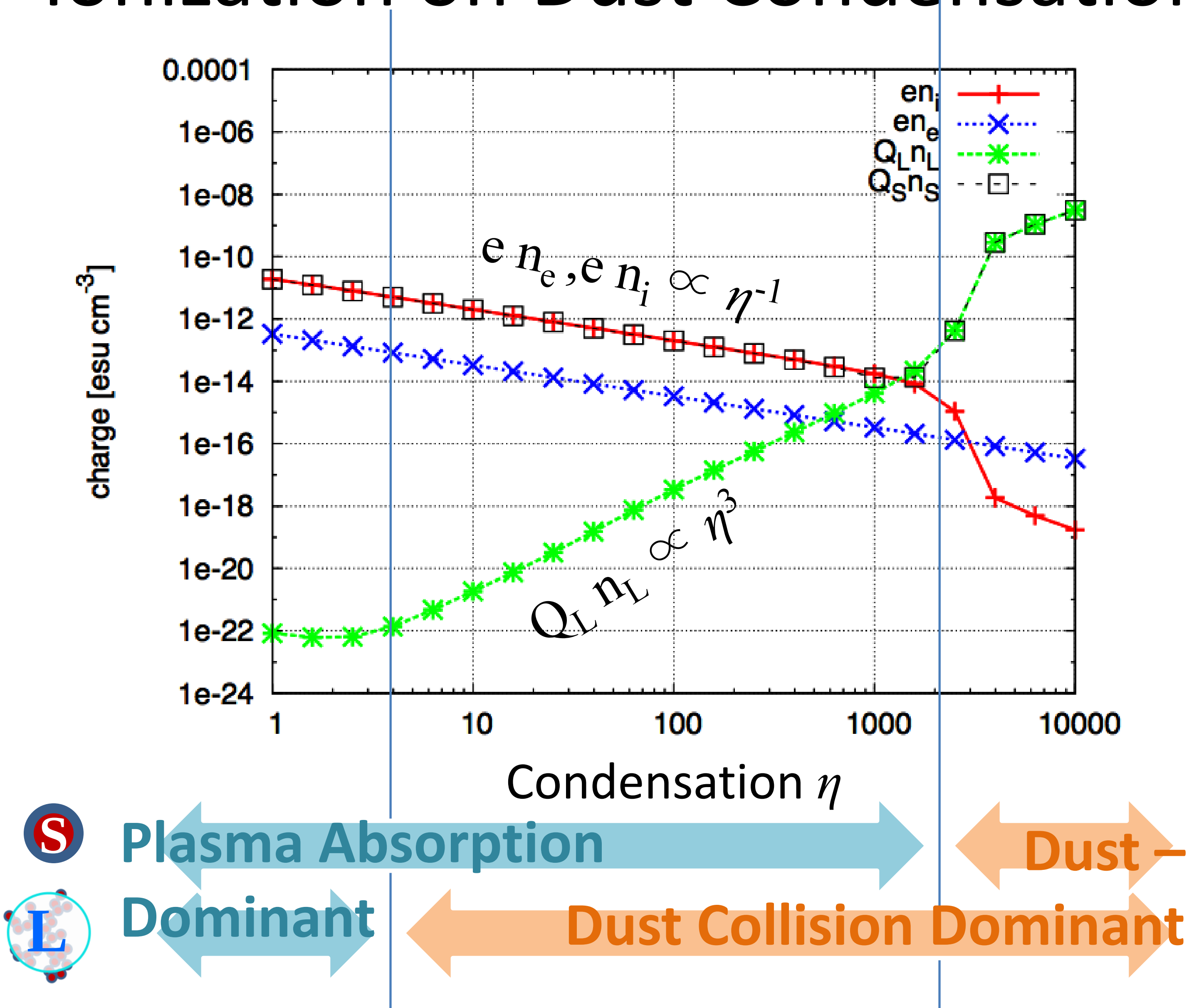
Q_L, Q_S : Charge per one Large dust, one Small dust

Δq (Q_L, Q_S): Collisional charge exchange between L and S

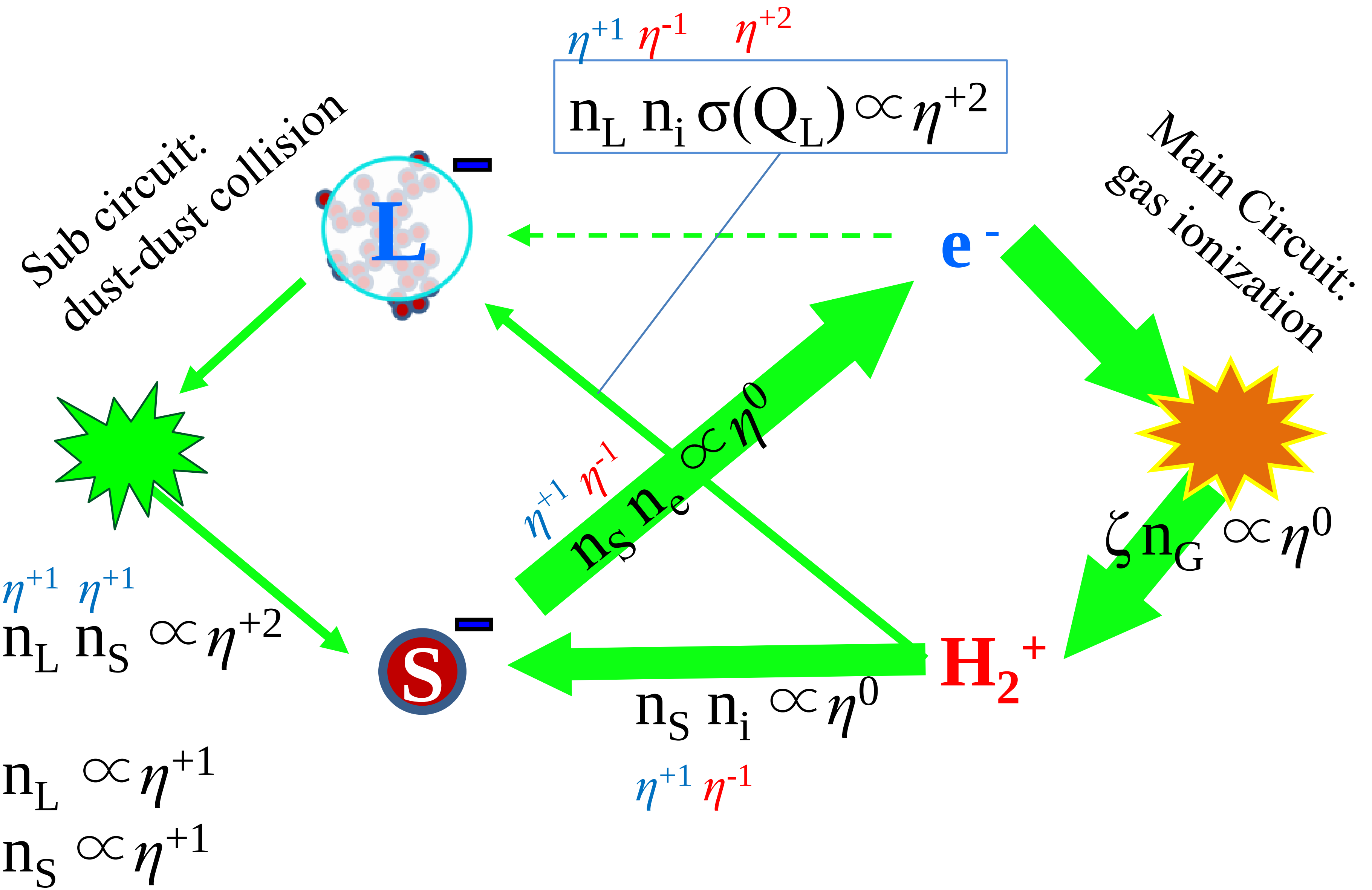
ζ : ionization ratio of the gas

η : Dust condensation; $m_S n_S = \eta \times 10^{-2} m_g n_g$, $m_L n_L = \eta \times 10^{-3} m_g n_g$

Dependence of Dust Charge and Ionization on Dust Condensation



The circuit model --- to derive η dependence of charge density



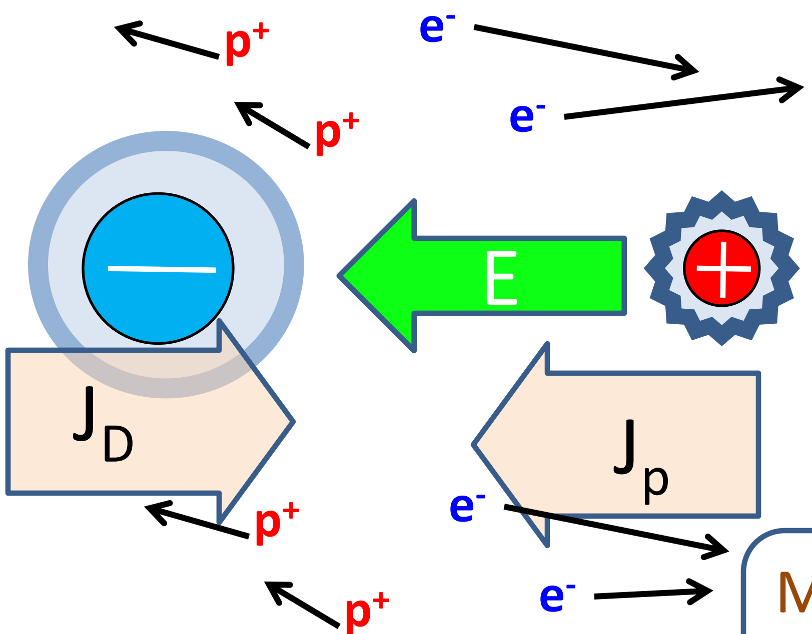
Conditions for Electric Breakdown in Dust Plasma

Condition for exponential ionization

$$e\,E_{\rm dis}\,l_{\rm mfp} = \Delta W_{\rm ion}$$

$$E_{\rm dis} = \frac{\Delta W_{\rm ion}}{e\,l_{\rm mfp}}$$

$\Delta W_{\rm ion}$ =15.4[eV]



Current by plasma and dust

$$j_D = Q_{_L} n_{_L} u_{_L}$$

$$j_p = \nu E_{\rm max}$$

$$\nu = \frac{n_e\,l_{\rm mfp}\,e^2}{m_e\,v_e}$$

Maximal electric field allowed in dust plasma

$$j_D = j_p$$

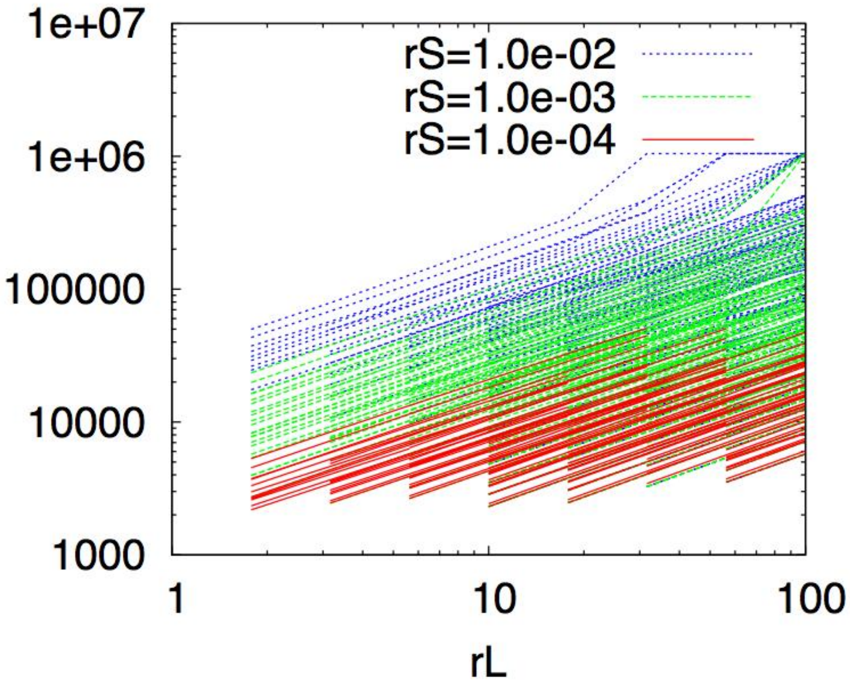
$$E_{\rm max} = \frac{m_e\,v_e\,Q_{_L}\,n_{_L}\,u_{_L}}{n_e\,l_{\rm mfp}\,e^2}$$

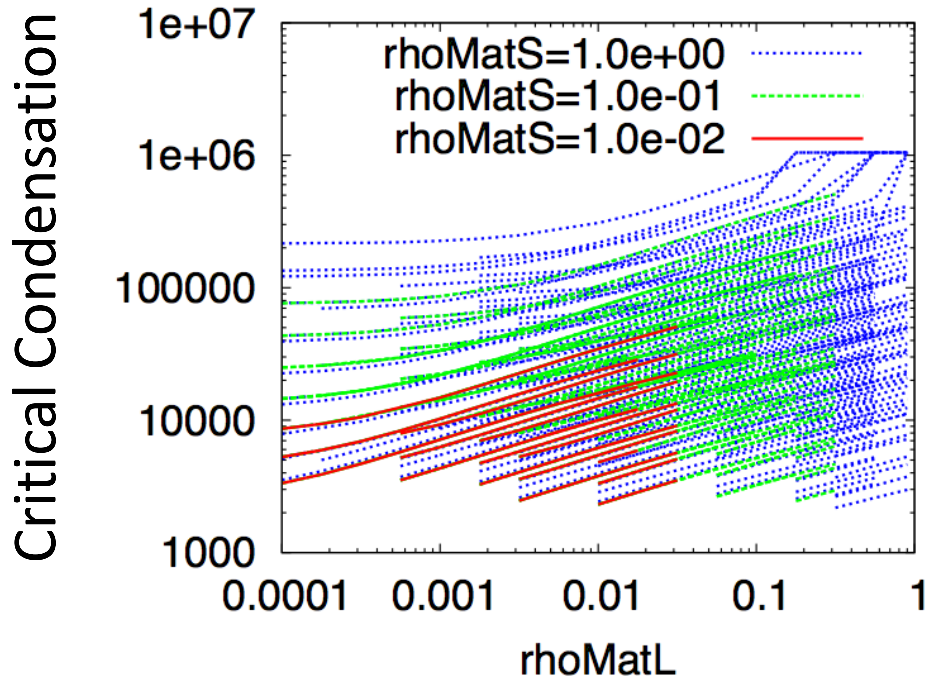
Condition for Electric Breakdown to occur in dust plasma

$$E_{\rm max} > E_{\rm dis}$$

$$\frac{Q_{_L} n_{_L}}{e\,n_e} > \frac{\Delta W_{\rm ion}}{m_e v_e u_{_L}}$$

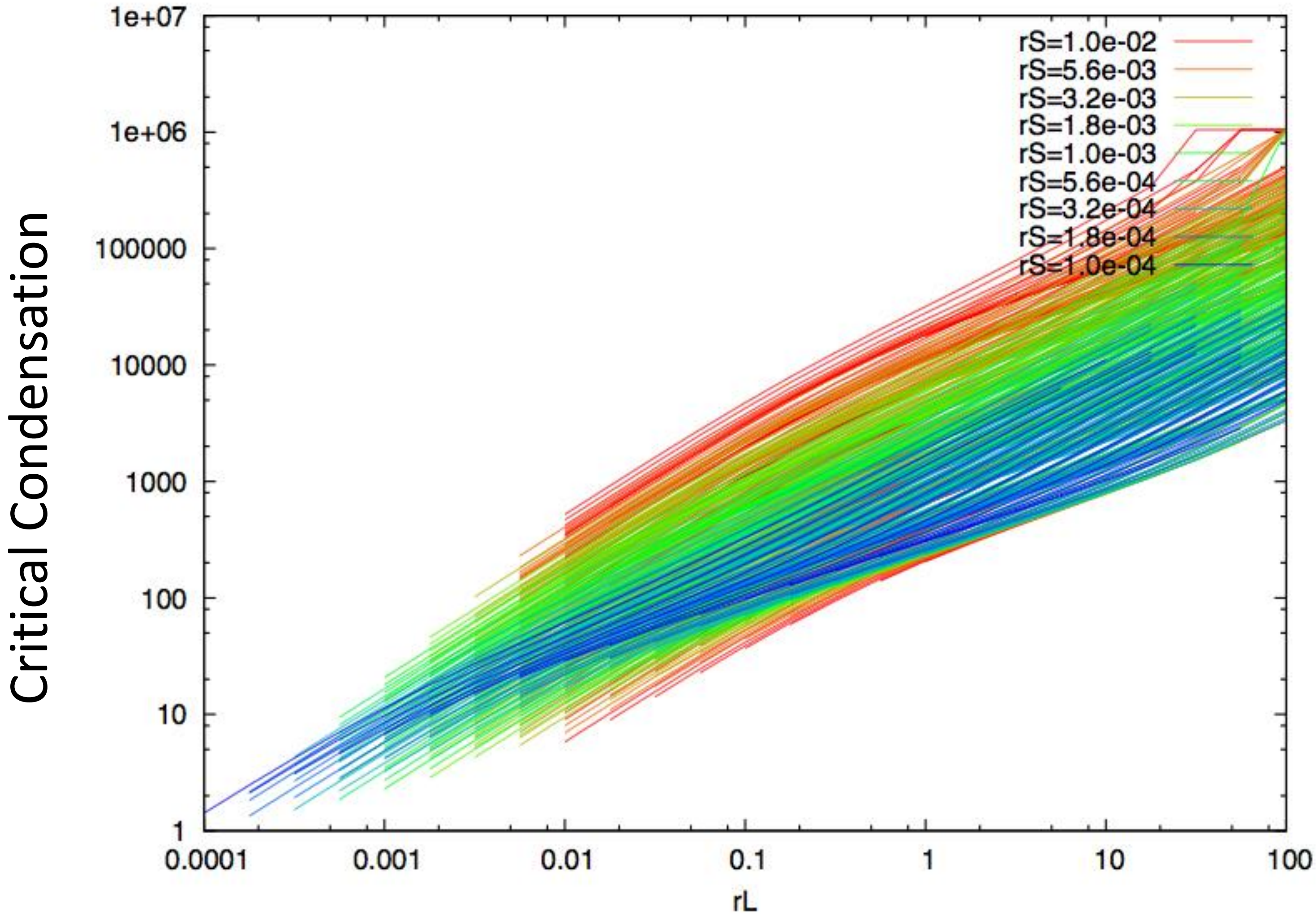
Condensation η for lightning to occur as function of r_L, r_S, ρ_L, ρ_S





- parameters are radius and material density of the Large and Small dust, r_L, r_S, ρ_L, ρ_S
- For each set of parameter search the minimum condensation η such that $m_e v_e u_L \frac{Q_L n_L}{e\, n_e} > \Delta W_{\rm ion}$
- Parameters are limited so that relative velocity > 50m/s

When you are free with constraint



Energetics of Lightning in Protoplanetary disks

- $E_{dis} \sim 5 \times 10^{-4}$ [G] electric field for e. > 15.4eV
- $E_{dis}^2/8\pi \sim 10^{-8}$ [erg/cm^3] energy density of *E*
- $h \sim 0.5 \times 10^{13}$cm scale height of the disk
- $W \sim 10^{30}$erg energy available for a lightning
- $v_e \sim 1.6 \times 10^8$ cm/s e. velocity for 15.4eV
- $t \sim 3 \times 10^4$ sec duration of lightning
- $l_{mfp} \sim 10^2$cm
- $R_{light} \sim 5000$mfp $\sim 5 \times 10^5$cm diameter of a lightning bolt (Pilipp et al. 1994)
- $\Delta T \sim 10^4$ K heating of neutral gas by lightning

Summary

- Dust – dust collision is necessary component in determining protoplanetary disk ionization if there is applicable dust condensation η
- The contribution increase as $\mathrm{Q_L\ n_L\ /\ e\ n_e} \propto \eta^4$
- The condition for lightning : $\frac{Q_L n_L}{e n_e} > \frac{\Delta W_{\mathrm{ion}}}{m_e v_e u_L}$
- Collision between dust of ice and other material is even more important
- Application to : Lightning observation, chondrule formation, planetesimal growth, MRI

Why most chondrule people gave up lightning as their heat source

- Chondrules are spherical sands (of radius ～mm) commonly seen in meteors. Chondrules experienced heating to 1800-2200K, melted, then cooled in several hours.
- Gibbard, Levy, and Morfill (1997) It is impossible to cause lightning by ice-ice collision.
- Guttler et al. 2008 : Lab experiment
- Lightning rarely heat dust to melting point (⇔high efficiency)
- Lightning is disruptive, rather than melting (⇔size distribution)

Why I don't give up

- $l_{mfp} \sim 10^2$cm in protoplanetary disk is drastically larger than any lab experiment can achieve
- l_{mfp} in lab < chrondrule size < l_{mfp} in space
- l_{mfp} < chrondrule size leads to localized current in chondrule → disruptive ??
- l_{mfp} > chrondrule leads to heating ??

The source of mean motion

- Migration
- Sedimentation is most hopeful???
- Large scale turbulence
- Streaming instability