Dust in Planetary Systems, Jena, 2010 With Opening Movies
25min

Electric Processes in Protoplanetary Disks

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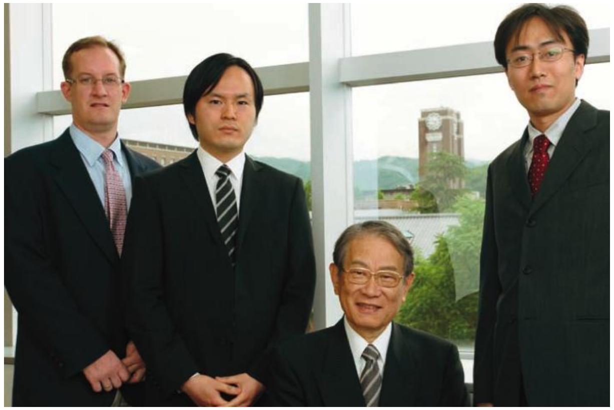
Part 0
The Science is in Crisis

The **Hakubi** Center, Kyoto University

Since 2010



- Unique, long-sighted, young researchers wanted from all the world, to save the science
- max. 20 people / year, 5 years position
- Natural Science, Social Science, Engineering… all OK
- Salary of Assistant Prof. / Associate Prof. + research funding
- No mid-career assessment & lay-off
- No education duty
- No PhD required to apply
- No tenure track

Dust–dust collisional charging and lightning in protoplanetary discs

Takayuki Muranushi

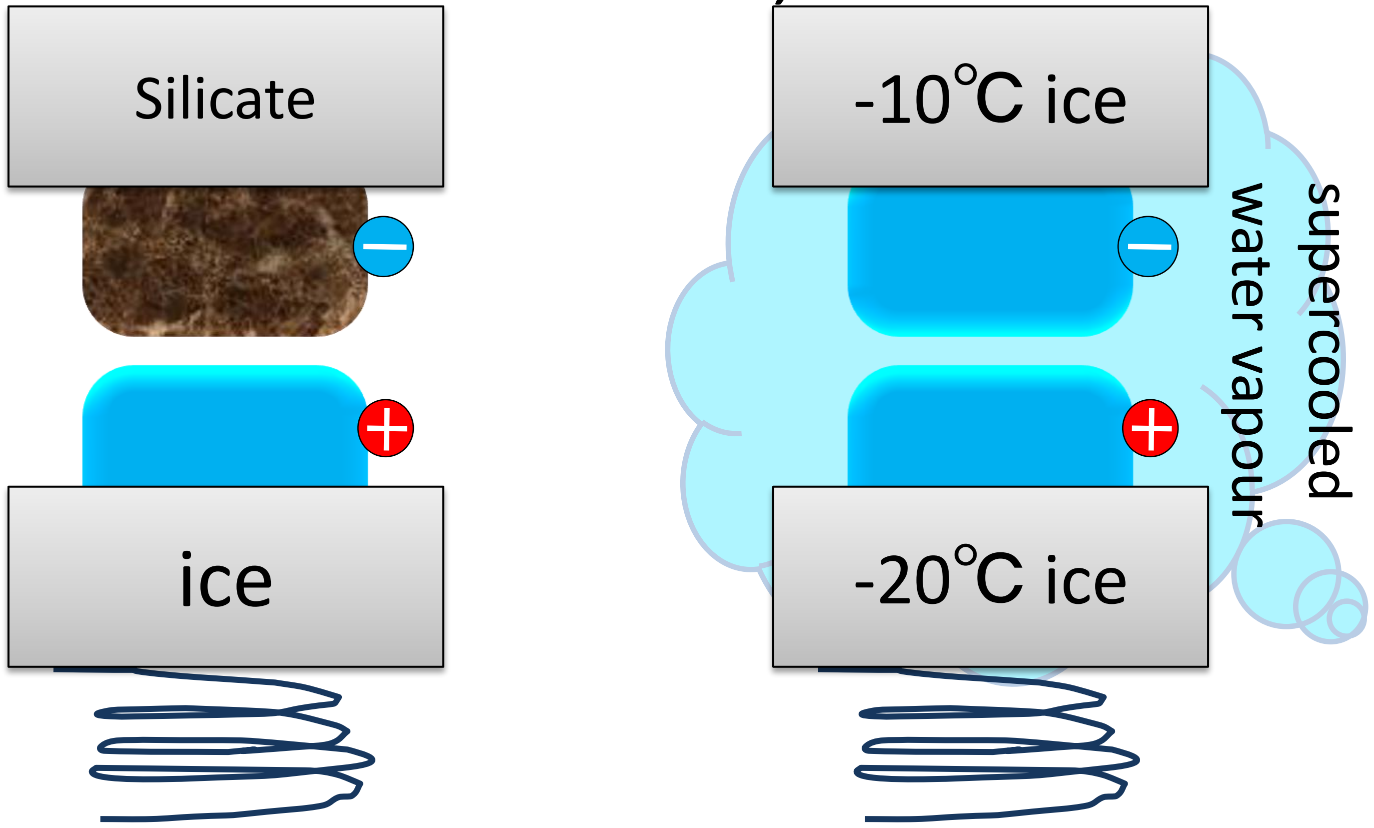
Mon. Not. R. Astron. Soc. 401,
2641–2664 (2010)

Part 1
Introduction To Lightning

Charging Mechanism Unique to Ice Surface, Crucial to **Lightning**

Gedankenexperiment

Experiments by Mason and Dash,2000



- Ice surface exchanges charge when collided together, or when collided with other materials

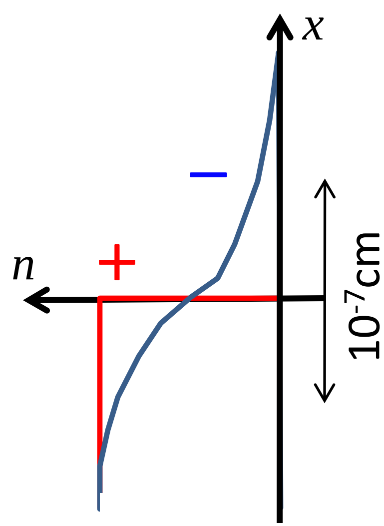
Charging Mechanisms for Solid Surface

Triboelectric Charge

- exchange of electron between matters due to different electron affinity
- Disk lightning mechanism candidate (Desch & Cuzzi, 2000)

Surface Charge

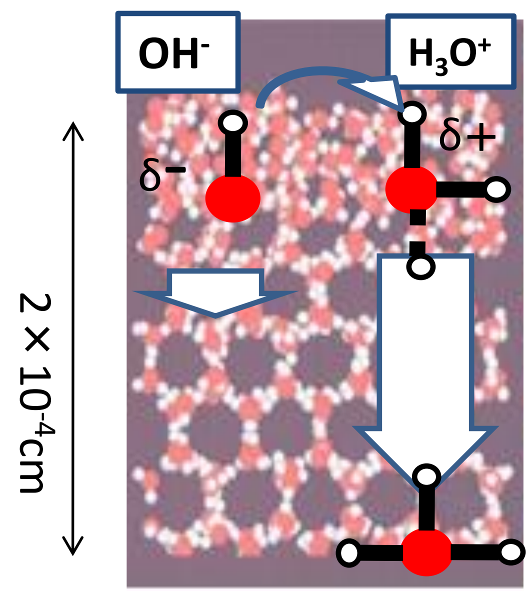
- free electron wave function spill-out
- widely seen in conductors and semiconductors (Somorjai 1994)

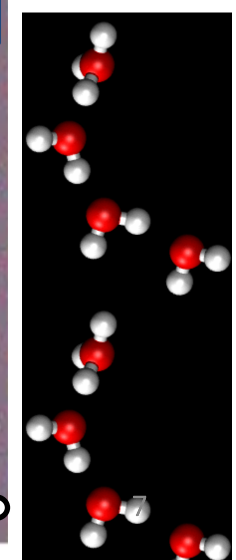


Ice Surface Charge

- charge transport by molecular ions H_3O^+
- Unique to H_2O (e.g. NH_3 lacks this mechanism: Goncalves+ 1999)
- deep, large separation

6.2×10^9 e cm^{-2}





★Lightning 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.

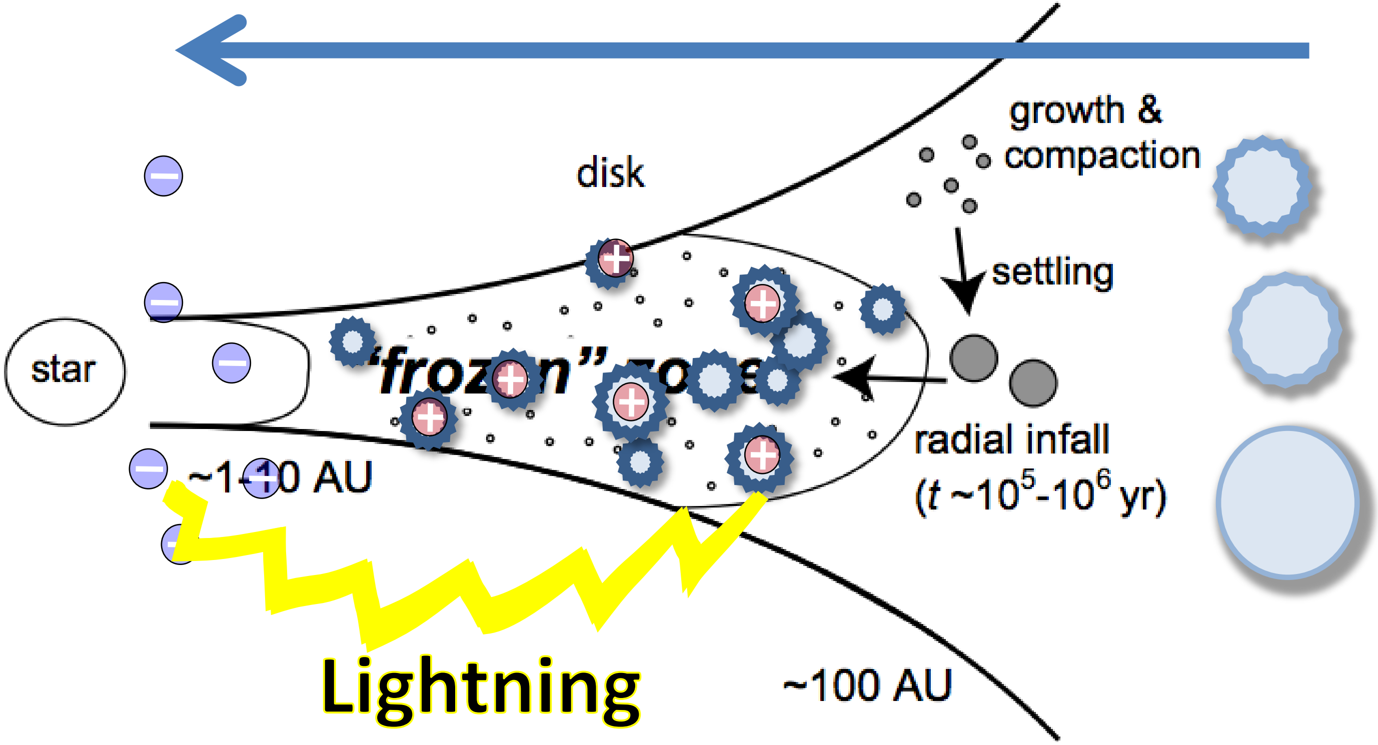
Charge Separation of ～ 50[C] ,
in height～km

(electric force ～ 1% of gravity)

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

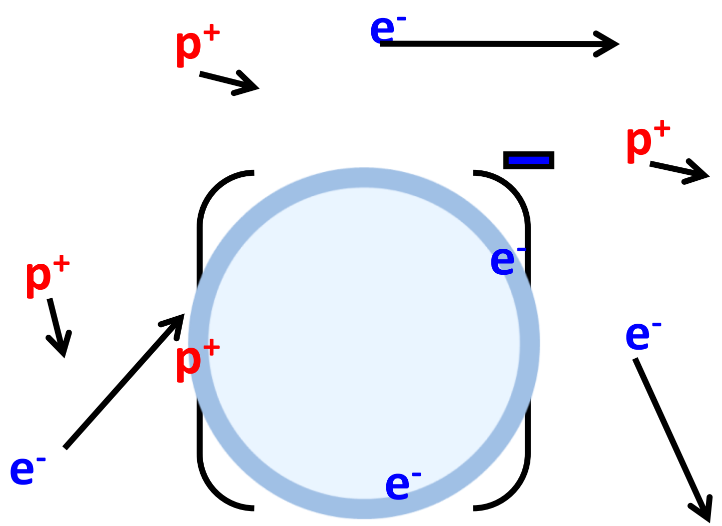
(From Okuzumi's Talk)

Radial drift may be a FRIEND of dust growth!

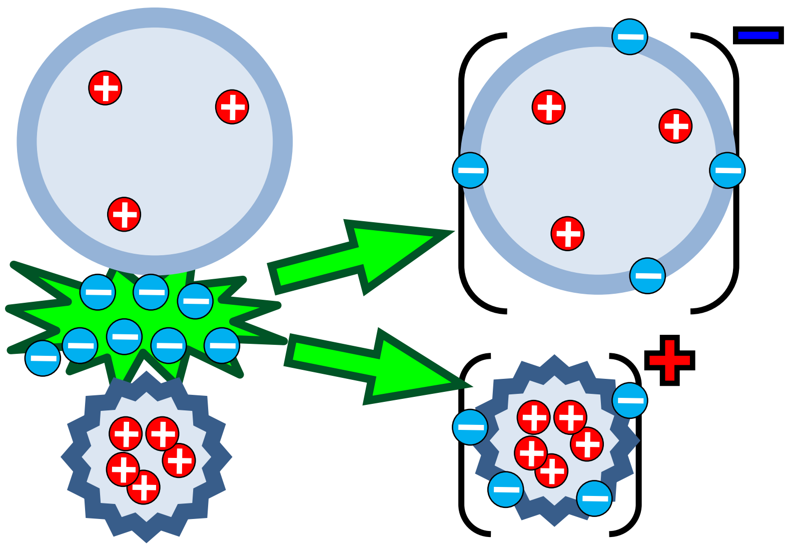


If so, collision of *very different-sized aggregates* will be important.

Dust Charging Processes in Protoplanetary Disks



Charge by plasma absorption (Okuzumi, 2009)

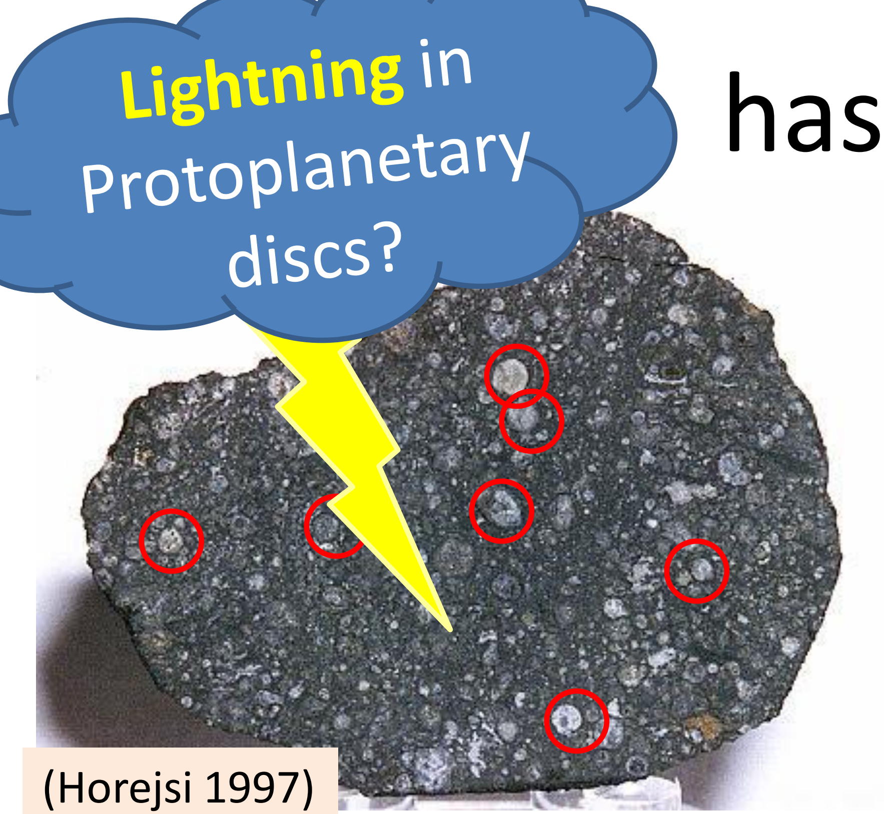


Charge by dust-dust collision (Gaskell et.al. 1978 …)

All dusts are weakly negative
Blocks the dust growth at μm stage

Dusts are charged in both sign, and very large compared to plasma absorption.

Part 2
Lightning in Protoplanetary Disks



(Horejsi 1997)

has long been studied

Chondrules
are silicate spherical grains of mm size, found today in wide area of our solar system. They are probably formed in protoplanetary nebula, when fluffy silicate dust aggregates are subject to ~1200K heat, melted, become spheric by surface tension, then frozen.

- as a candidate mechanism of chondrule heating
- Literatures generally says that **lightning do not take place**, or do not contribute to chondrule formation.
- There are problems …

Three Problems against Lightning and Chondrule Formation by Lightning

①Neutralization Problem (Gibbard ,Levy & Morfill 1997)

- Lightning do not occur. Since PPD is weakly ionized and conductive, and dust is few, generated E field is too weak. $E \propto n^2$ so you need unnaturally high dust number density.

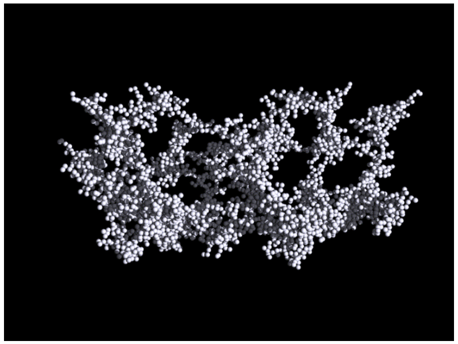
②Energetics Problem (e.g. Weidenschilling 1997)

- If lightning do occur, it isn’t energetic enough to melt all the chondrules observed today, because the budget is turbulent energy --- a little portion of total kinetic energy

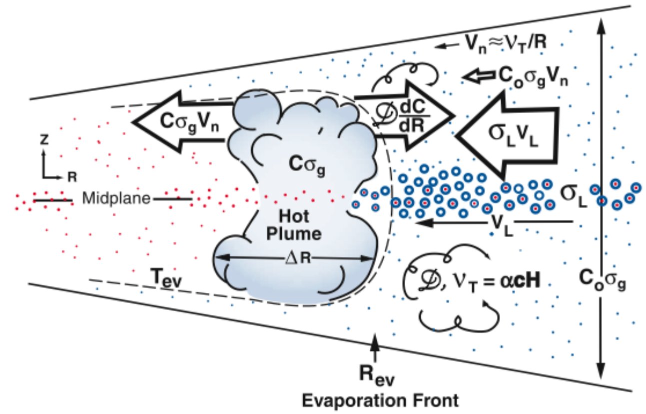
③Destruction Problem (Güttler+ 2008)

- If lightning do occur, experiments show that it destroys the dust aggregates rather than melts them.

New pictures in protoplanetary disc



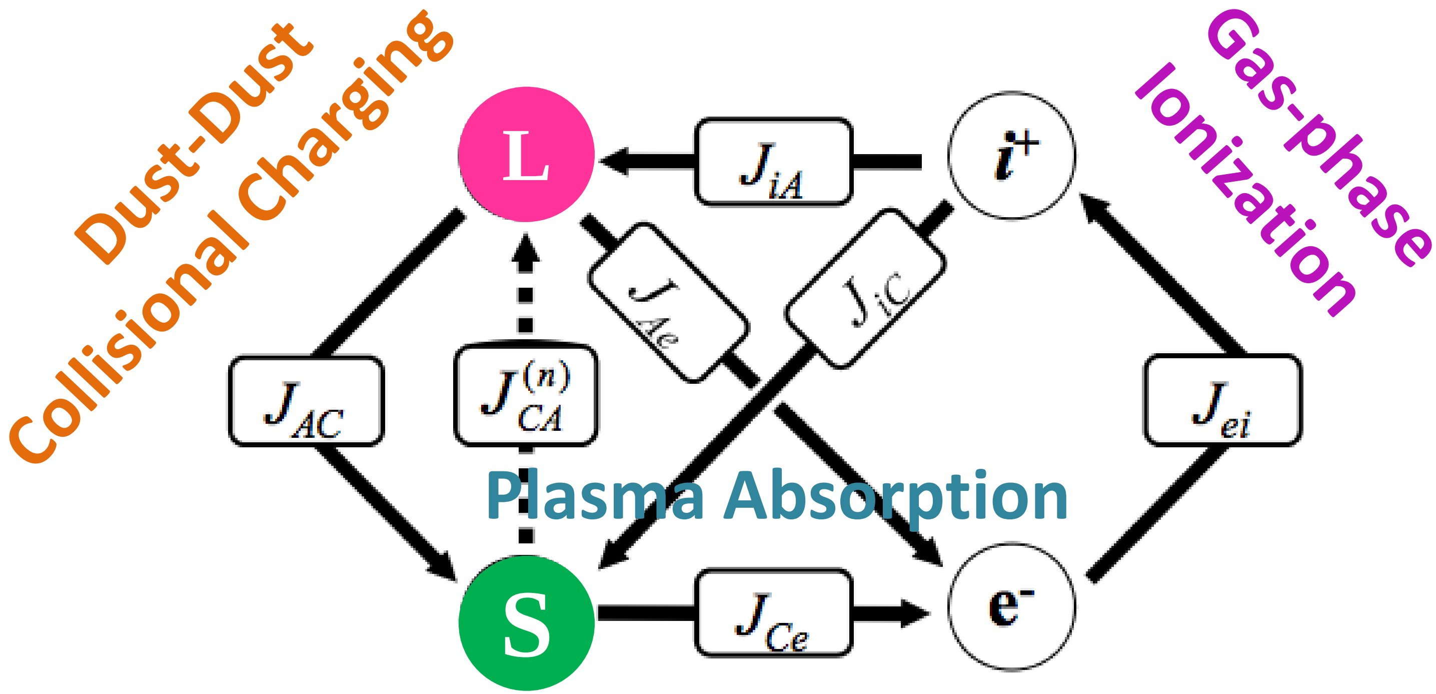
Suyama, Wada et.al. ,2007



Cuzzi & Zahnle, 2003

- Dust aggregates are fluffy (low fractal dimension).
- Regions with higher dust number density than MMSN are possible. Disks with more dust are found
  - e.g. 3×10^{-3} M_{SUN} dust for a $0.5M_{SUN}$ star, Sauter+ 2009
- Let us take these into consideration and re-estimate if lightning do take place (Muranushi, 2010)
- **Default location is 2.7AU@MMSN equatorial**

The ‘Circuit’ within protoplanetary disk



- Large dust(L); Small dust(S); ions(i); electrons(e); are involved
- In this talk e.g. Small dust(S) is Cationic (receives positive charge from collision); Large dust(L) is Anionic. The other polarity is also possible.

Estimation of Currents[esu cm^{-3} s^{-1}]

Gas-phase Ionization

$$J_{\mathrm{i,e}} = -e\zeta n_{\mathrm{g}}.$$

where

$\zeta = 10^{-18}$ (Umebayashi & Nakano, 2009)

$$\sigma_{\mathrm{Cou}}(q) = \pi a^2 \exp\left(-\frac{qq'}{ak_{\mathrm{B}}T}\right) \qquad (qq' > 0),$$

$$\sigma_{\mathrm{Cou}}(q) = \pi a^2 \left(1 - \frac{qq'}{ak_{\mathrm{B}}T}\right) \qquad (qq' < 0)$$

Plasma Absorption

$$J_{\mathrm{L,i}} = -Q_{\mathrm{i}} n_{\mathrm{L}} \sigma_{\mathrm{Cou}}\left(\frac{Q_{\mathrm{L}}}{n_{\mathrm{L}}}, e, r_{\mathrm{L}}, k_{\mathrm{B}}T\right) v_{\mathrm{i}}$$

$$J_{\mathrm{L,e}} = -Q_{\mathrm{e}} n_{\mathrm{L}} \sigma_{\mathrm{Cou}}\left(\frac{Q_{\mathrm{L}}}{n_{\mathrm{L}}}, -e, r_{\mathrm{L}}, k_{\mathrm{B}}T\right) v_{\mathrm{e}}$$

$$J_{\mathrm{S,i}} = -Q_{\mathrm{i}} n_{\mathrm{S}} \sigma_{\mathrm{Cou}}\left(\frac{Q_{\mathrm{S}}}{n_{\mathrm{S}}}, e, r_{\mathrm{S}}, k_{\mathrm{B}}T\right) v_{\mathrm{i}}$$

$$J_{\mathrm{S,e}} = -Q_{\mathrm{e}} n_{\mathrm{S}} \sigma_{\mathrm{Cou}}\left(\frac{Q_{\mathrm{S}}}{n_{\mathrm{S}}}, -e, r_{\mathrm{S}}, k_{\mathrm{B}}T\right) v_{\mathrm{e}}$$

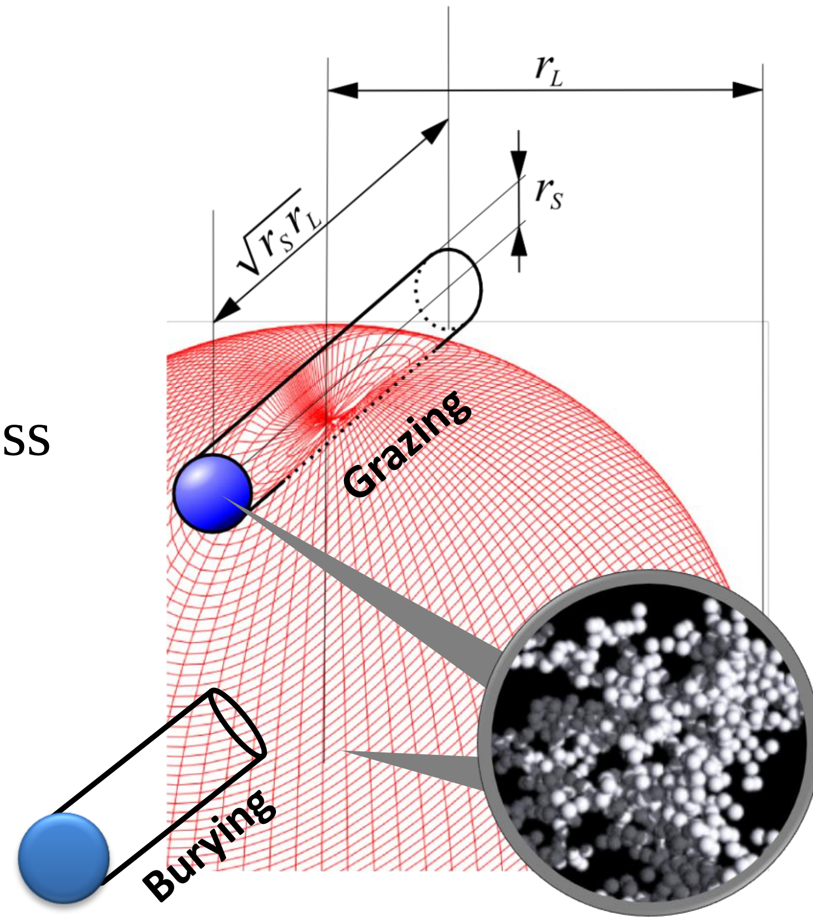
Dust-Dust Collisional Charging and Collisional Neutralization

Three particles involved: fractal dimension and radius

Large dust: D_{L} , r_{L}

Small dust: D_{S} , r_{S}

Monomer : r_{m}



Grazing collision →charge separation cross section : $\sigma_{\mathrm{SL}} = r_{\mathrm{S}}\, r_{\mathrm{L}}$

Burying collision →neutralization cross section : $\sigma_{\mathrm{SL(N)}} = r_{\mathrm{L}}^{\,2}$

Relative velocity: v_{SL}

Event rate for grazing collision:

$\sigma_{\mathrm{SL}}\, n_{\mathrm{S}}\, n_{\mathrm{L}}\, v_{\mathrm{SL}}$ [cm^{-3} s^{-1}]

Dust-Dust Collisional Charging and Collisional Neutralization 2

Ice crystal surface charge density : σ_{ch} = 6.2 × 10^9 [e cm^{-2}]
Charge exchange efficiency : η_{ch} = 10^{-1}

(c.f. Dash et.al. 2001)

Ice surface involved in contact : smaller of

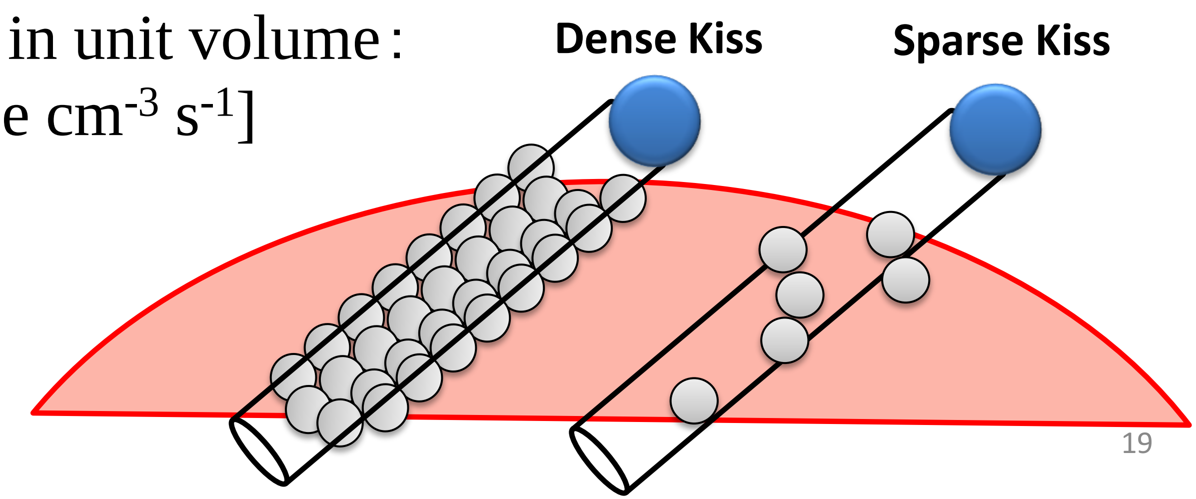
- $S_{kiss} = r_S^{\ 3/2}\, r_L^{\ 1/2}$ [cm^{-2}] L-dust is dense
- $S_{kiss} = r_m^{\ 2-DL}\, r_S^{\ 5/2}\, r_L^{\ DL-5/2}$ [cm^{-2}] L-dust is sparse

Charge separated by single collision event :

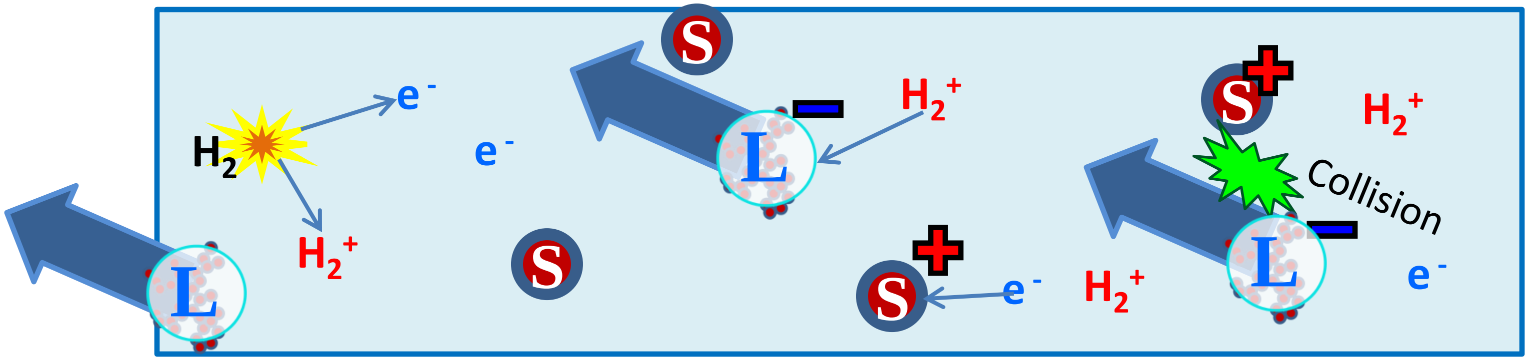
$\triangle q = \sigma_{ch}\, \eta_{ch}\, S_{kiss}$ [e]

Charge separation ratio in unit volume :

$J_{SL} = \triangle q\, \sigma_{SL}\, n_S\, n_L\, v_{SL}$ [e cm^{-3} s^{-1}]



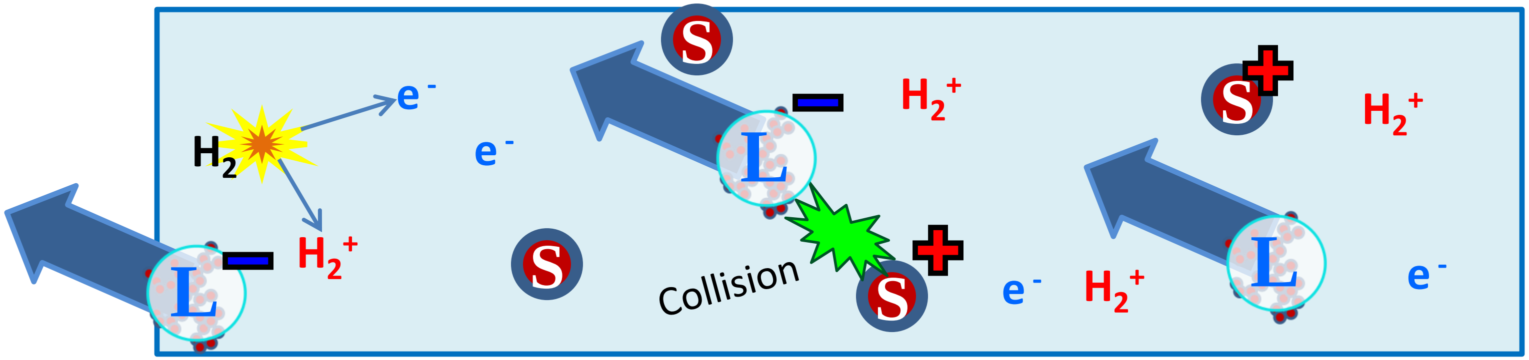
An Ice-Dust Charge Model with Dust-Dust Collision Taken into Account



- Solve charge exchange equilibrium of four components : Large dust(L); Small dust(S); ions(i); electrons(e) in **Local Box (zero-dimensional) model**. Gas phase ionization, plasma absorption to dust, dust-dust collision are considered.
- Large dust has some mean motion to other components and carries electric current; plasma creates neutralizing current and Electric field is determined by Ohm's law.
- Dust space density is N times that of MMSN model :

$$\rho_S = N \times 10^{-2} \rho_g \,,\ \rho_L = N \times 10^{-3} \rho_g$$

Calculating Dust Charge with Dust-Dust Collision Taken into Account



- Parametes are: dust aggregate radius $\boldsymbol{r}_{\mathrm{S}}, \boldsymbol{r}_{\mathrm{L}}$; fractal dimension $\boldsymbol{D}_{\mathrm{S}}, \boldsymbol{D}_{\mathrm{L}}$; nondimensional dust density N

  $\rho_S = N \times 10^{-2} \rho_{\mathrm{g}}$, $\rho_{\mathrm{L}} = N \times 10^{-3} \rho_{\mathrm{g}}$

  $N = 100$: Equal mass of dust and gas per volume

- Unknowns are: charge density of each component $\boldsymbol{Q}_{\mathrm{I}}$ ($\boldsymbol{r}_{\mathrm{S}}, \boldsymbol{r}_{\mathrm{L}}, \boldsymbol{D}_{\mathrm{S}}, \boldsymbol{D}_{\mathrm{L}}; N$) Electric field: E ($\boldsymbol{r}_{\mathrm{S}}, \boldsymbol{r}_{\mathrm{L}}, \boldsymbol{D}_{\mathrm{S}}, \boldsymbol{D}_{\mathrm{L}}; N$)

- **The First Question** : How does charge distributions $\boldsymbol{Q}_{\mathrm{i}}$, $\boldsymbol{Q}_{\mathrm{e}}$, $\boldsymbol{Q}_{\mathrm{S}}$, $\boldsymbol{Q}_{\mathrm{L}}$, Electric field: E ,change as dust number density is increased?

Charge Evolution Equation for Dust Plasma

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

Dust-dust collision/neutralization

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

Plasma absorption

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

Gas phase ionization

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

Calculate Equilibrium Solutions $Q_{\mathrm{I}}\,(r_{\mathrm{S}}, r_{\mathrm{L}}, D_{\mathrm{S}}, D_{\mathrm{L}}; N)$ and their N dependence

n_{I} : number densities ($\mathrm{I} = \mathrm{L}, \mathrm{S}, i, e, g$)

q_L, q_S : charge per patricle

$\Delta q\ (q_L, q_S)$: amount of charge exchanged in a single dust-dust collision event

ΔV_{LS} : relative velocity between large and small dust, default = 3400cm/s

ζ : gas ionization ratio

N : nondimensional dust density : $\rho_S = N \times 10^{-2} \rho_g$, $\rho_L = N \times 10^{-3} \rho_g$

Charge distribution of dust plasma

had two phase, when dust-dust collision doesn't do anything tricky

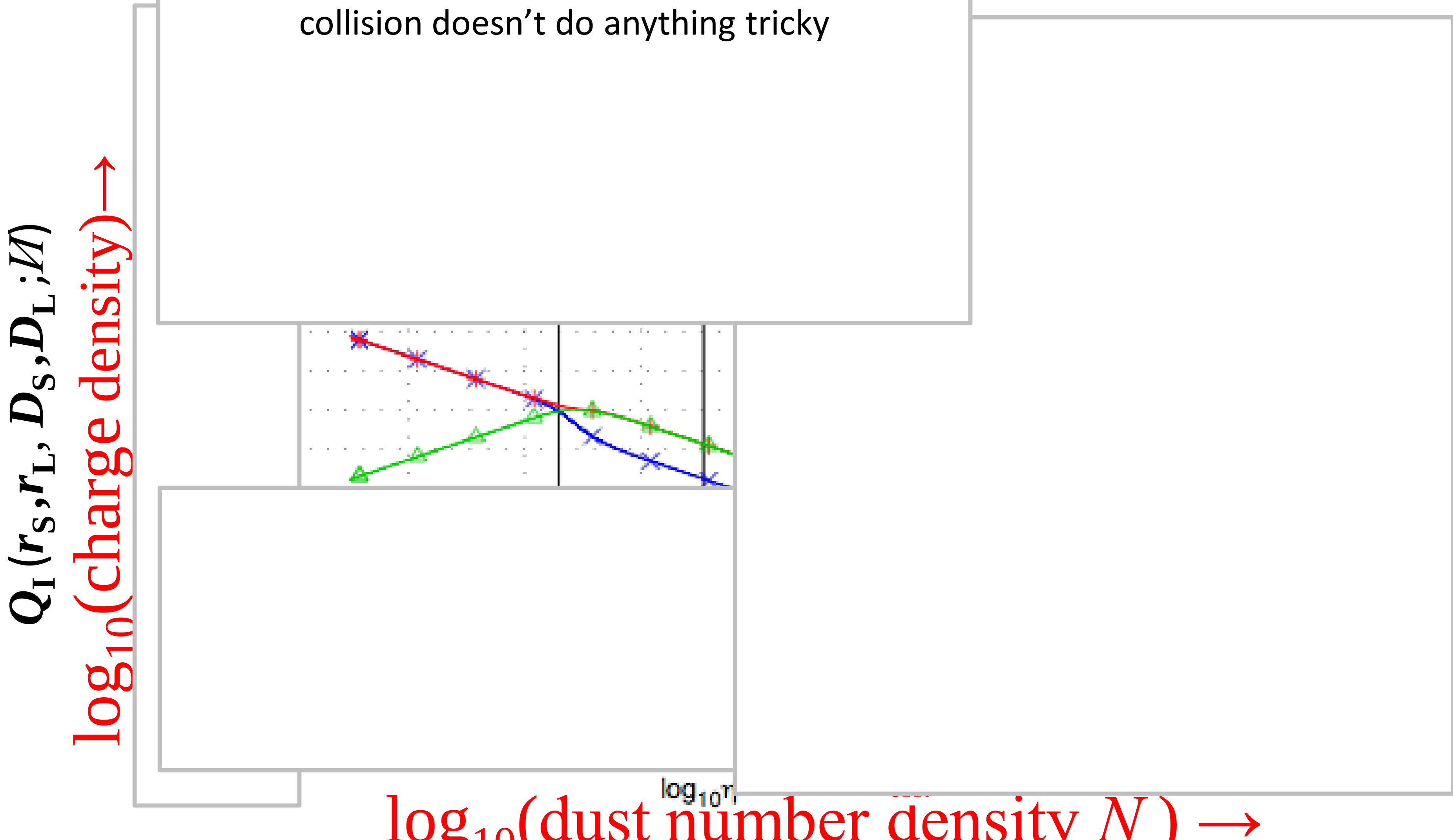
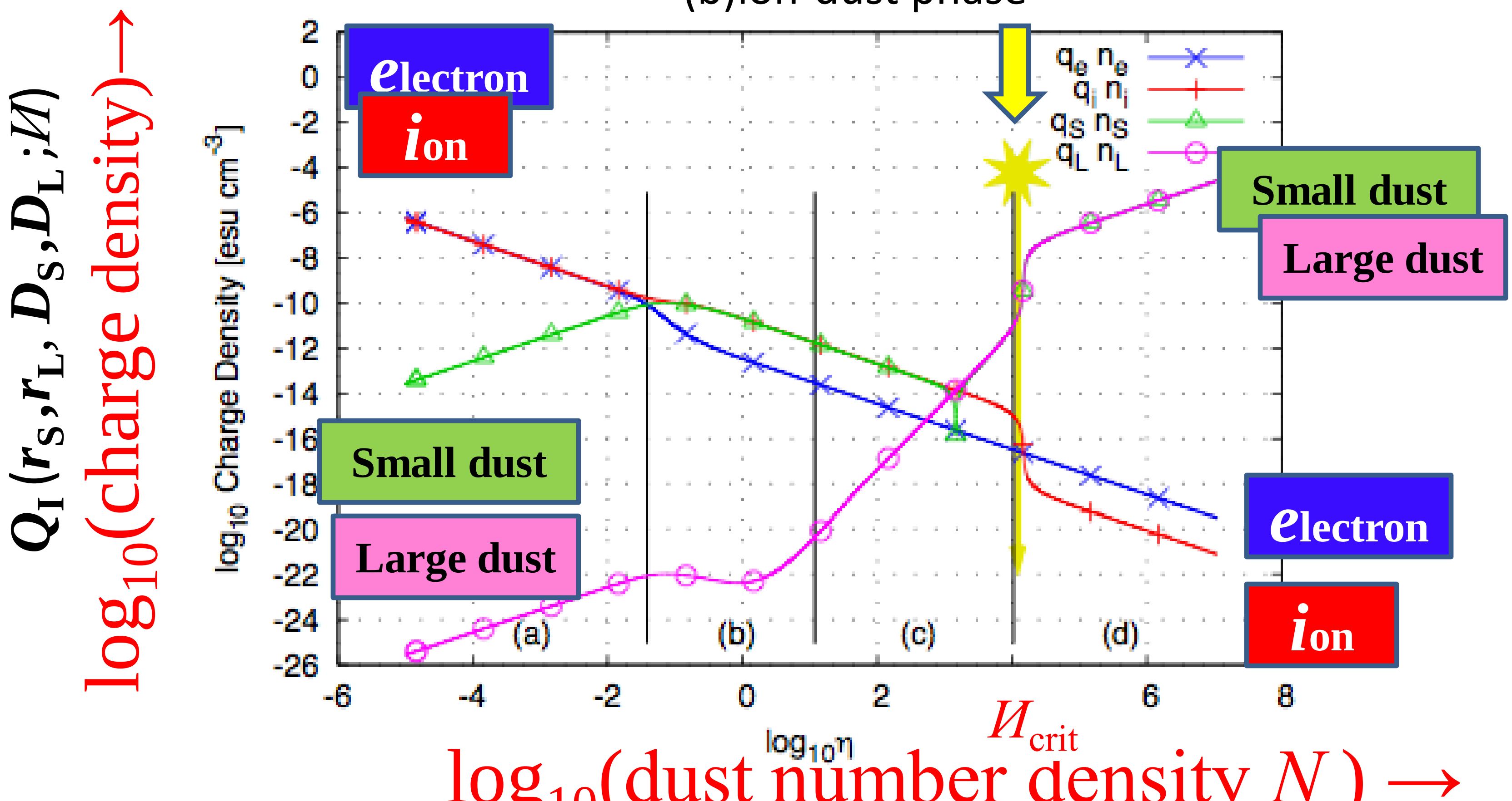


Figure 3. Amount of charge stored in each species, en_e, en_i, $|q_S|n_S$, and $|q_L|n_L$, as function of η. This figure is for ice dust-ice dust case, so boulder is anionic and sand is cationic. The

Charge distribution of dust plasma has four phase

(a)ion-electron phase (c)charge-up phase

(b)ion-dust phase (d)dust phase



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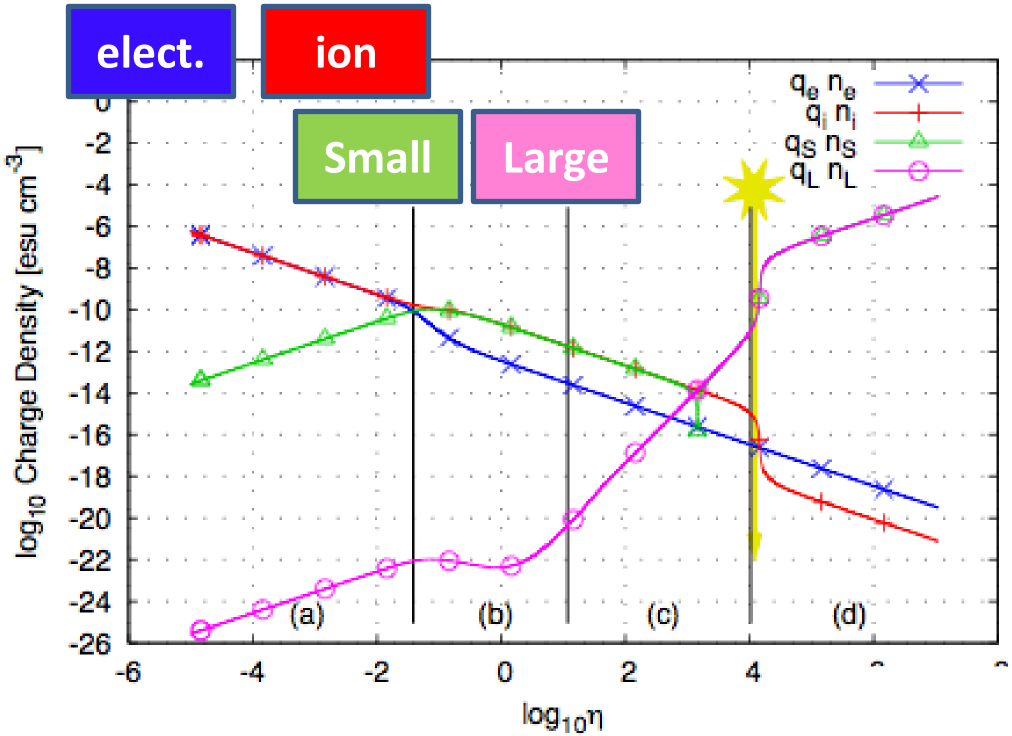
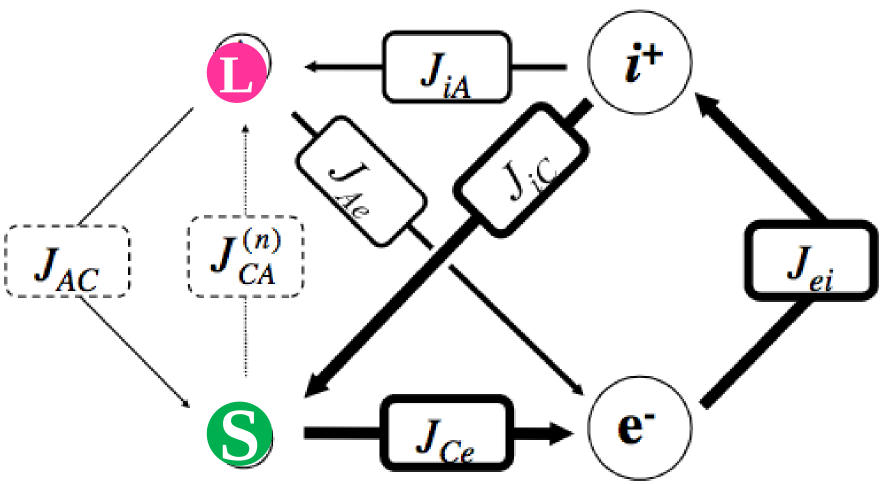
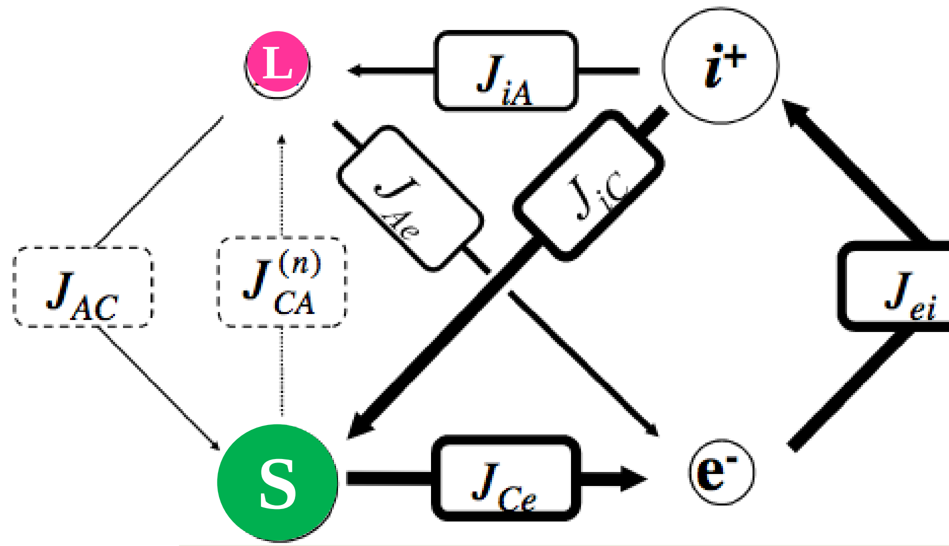


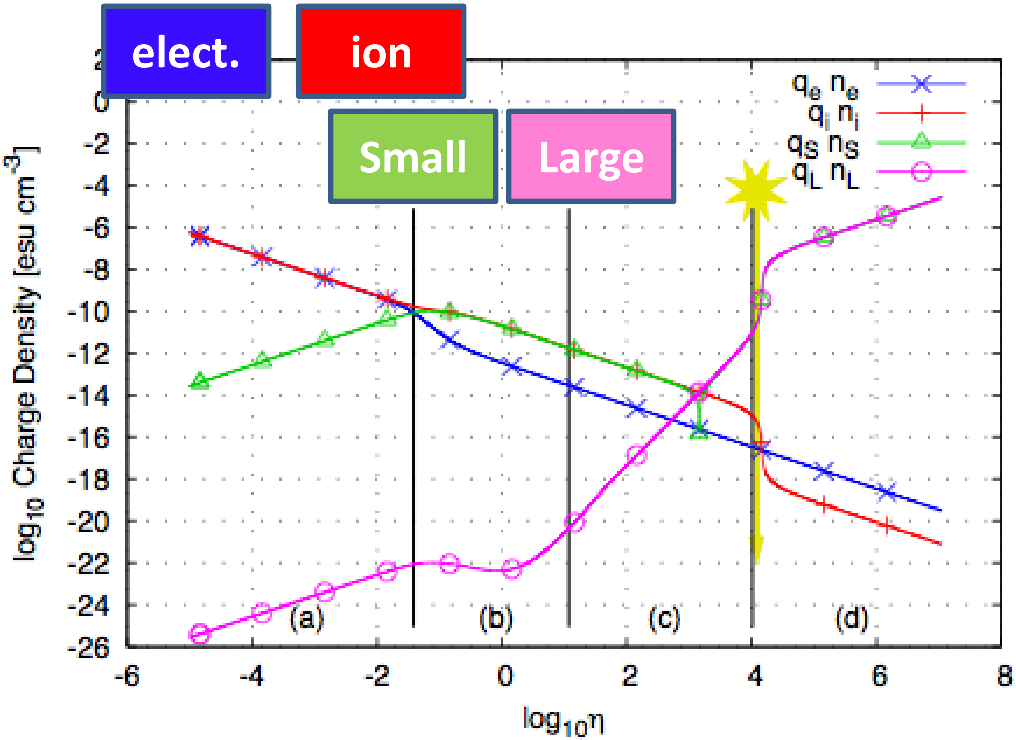
- (a) Ion-Electron Plasma Phase : all dust have weak negative charge
- (b) Ion-Dust Plasma Phase : Small dust carries main negative charge



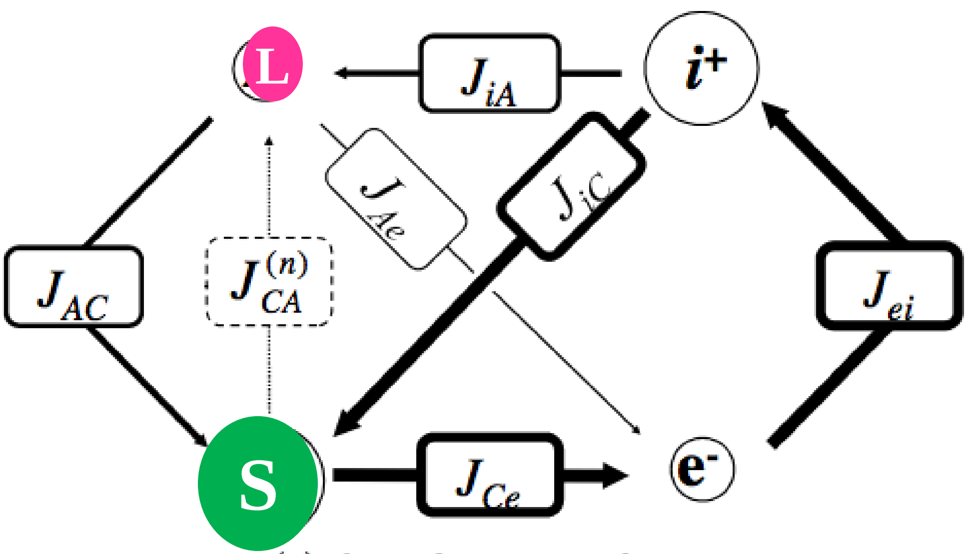
(a) Ion-Electron Plasma Phase



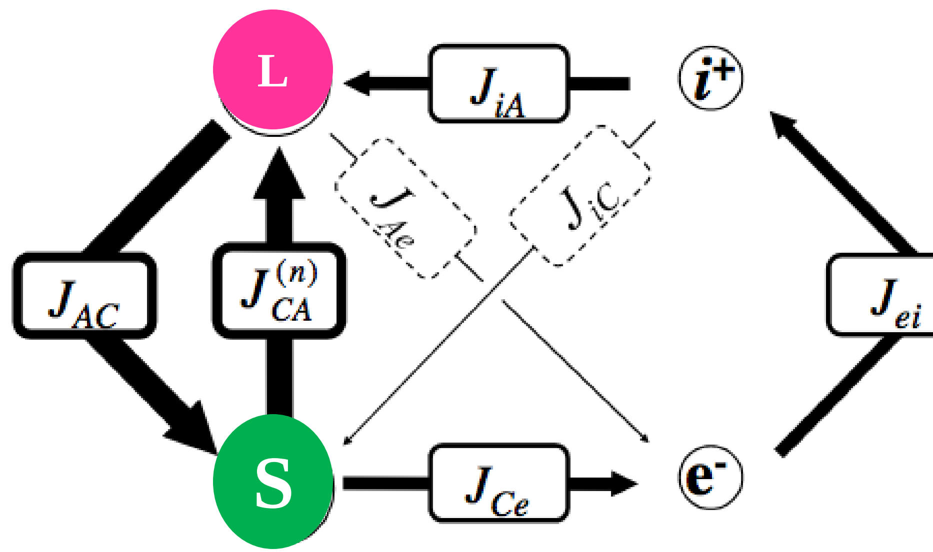
(b) Ion-Dust Plasma Phase



- (c) Chage-up Phase: $Q_{\mathrm{L}} \propto N^3$ and $E \propto N^4$
- (d) Dust Phase: Collisional charge separation > cosmic ray charge separation.
- In most case lightning takes place at (c)-(d) boundary.



(c) Charge-up Phase



(d) Dust Phase

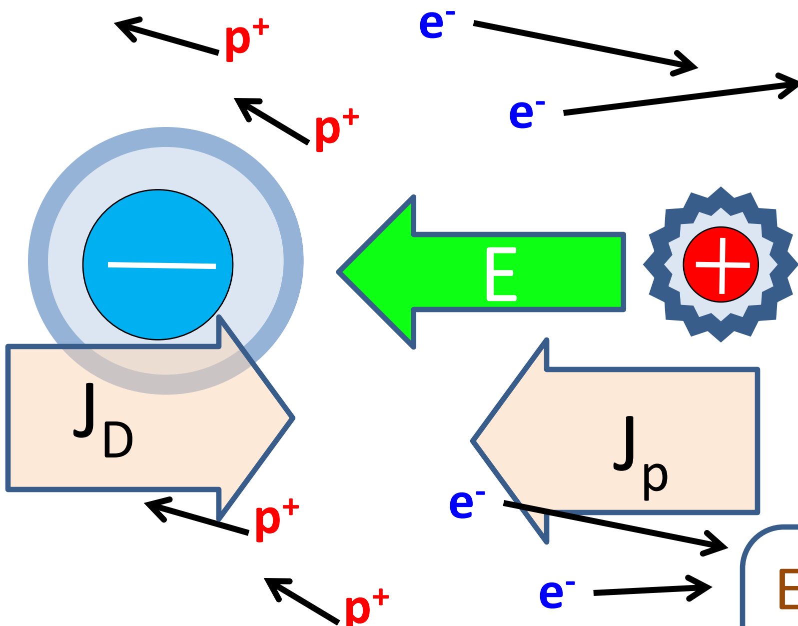
Electric field generated by dust motion

Electrostatic breakdown condition

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

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

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



Dust & plasma currents

$$j_D = q_L\, n_L\, u_L$$

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

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

Electric field determined by Ohm's Law

$$j_D = j_p$$

$$E_{\rm mhd} = \frac{m_e\, v_e\, q_L n_L\, u_L}{n_e\, l_{\rm mfp}\, e^2}$$

Condition for lightning

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

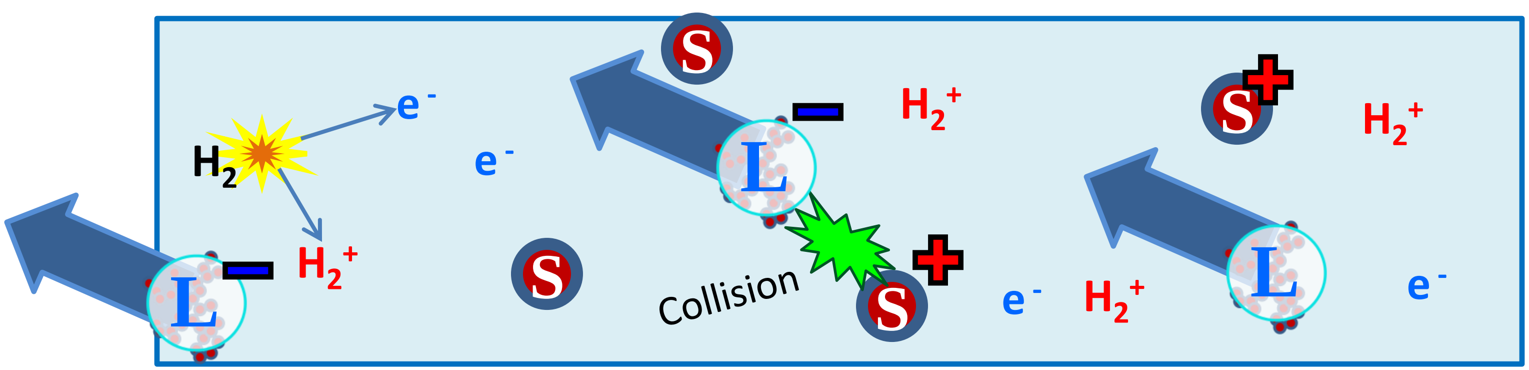
$$\frac{q_{L,} n_L}{e\, n_e} > \frac{\Delta W_{\rm ion}}{m_e v_e u_L}$$

Charge density by Large dust / Charge density by electron

greater than a constant

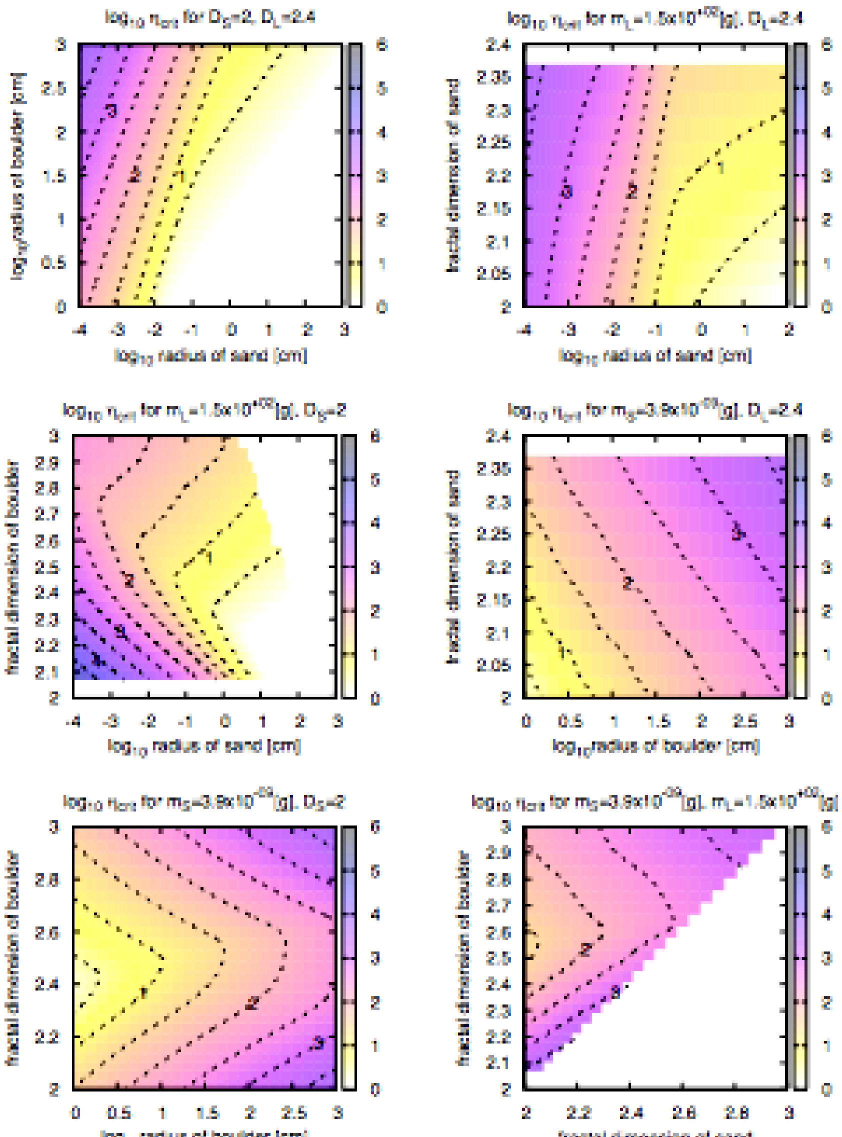
The Second Question: $N_{\rm crit}(r_{\rm S}\,, r_{\rm L}, D_{\rm S}\,, D_{\rm L})$?

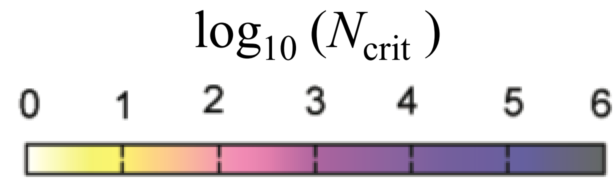
- Lightning takes place if dust number density larger than $N_{\rm crit}$ (in unit of MMSN)
- The Second Problem: calculate $N_{\rm crit}$ as a function of dust radii ($r_{\rm S}\,, r_{\rm L}$) and fluffiness ($D_{\rm S}\,, D_{\rm L}$)



$N_{crit}(r_S, r_L, D_S, D_L)$

2D cross sections of 4D plot



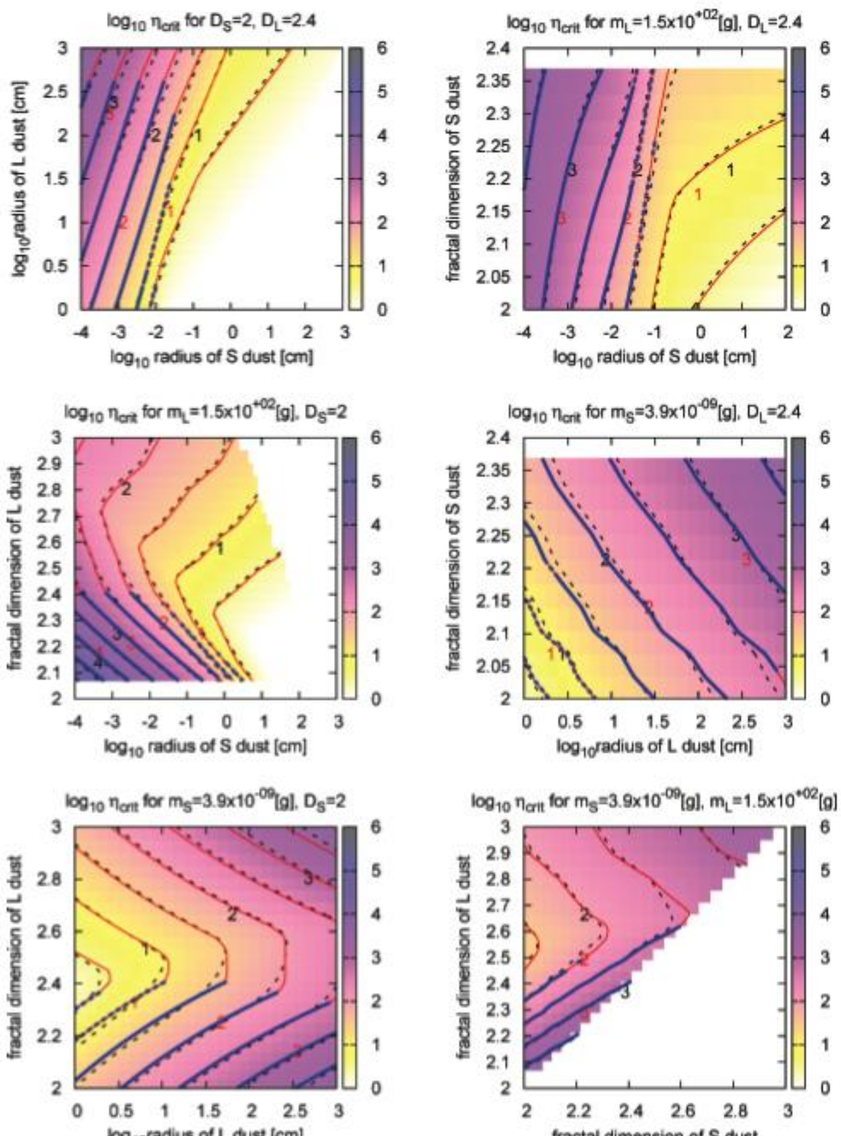


r_S [cm]	r_L [cm]	D_S	D_L	N_{crit}
10^{-2}	10^{2}	2.0	2.4	73
10^{-4}	10^{0}	2.0	3.0	90
10^{-2}	10^{2}	2.0	2.6	26

And how I made this simulation 100’000 times faster … that’s another story.

Solver	Number of cases	Time	Optimization
Direct integral, CPU[a]	9885	636 714	1.0
Binary search, CPU[b]	19 200	977.973	1.3×10^3
Binary search, GPU[c]	19 200	6.987 05	1.8×10^5
Final problem[d]	364 325	226.469	1.0×10^5

analytic form for $N_{\rm crit}$ accurate & precise!



$$
\begin{aligned}
\eta_{\rm crit} &= \eta^{\rm (d)}_{\rm crit} \quad \text{if } \eta^{\rm (d)}_{\rm crit} > \eta^{(cd)}, \\
&= \eta^{(cd)} \quad \text{if } \eta^{\rm (c)}_{\rm crit} > \eta^{(cd)} > \eta^{\rm (d)}_{\rm crit}, \\
&= \eta^{\rm (c)}_{\rm crit} \quad \text{otherwise.}
\end{aligned}
\tag{122}
$$

simulation results: colour map & dashed contour

analytic formulae: colour contour

Only 3 uncertain parameters in analytic formulae: fits 364’325 points with 9.2% precision!

$$
\begin{aligned}
\eta^{\rm (c)}_{\rm crit} = 1.1\times10^{3} &\left(\frac{\Delta q_{\rm A,C}}{6.2\times10^{2}\,{\rm e}}\right)^{-\frac{1}{4}} \left(\frac{n_{\rm g}}{4.7\times10^{13}\,{\rm cm^{-3}}}\right)^{\frac{1}{2}} \\
&\left(\frac{n_{\rm S}^{\bowtie}}{8.8\times10^{-1}\,{\rm cm^{-3}}}\right)^{-\frac{3}{4}} \left(\frac{n_{\rm L}^{\bowtie}}{4.0\times10^{-14}\,{\rm cm^{-3}}}\right)^{-\frac{1}{4}} \\
&\left(\frac{r_{\rm S}}{1.0\times10^{-4}\,{\rm cm}}\right)^{-\frac{5}{4}} \\
&\left(\frac{\zeta}{1.0\times10^{-18}\,{\rm s^{-1}}}\right)^{\frac{1}{2}} \\
&\left(\frac{\Delta v_{\rm L,S}}{3.4\times10^{3}\,{\rm cm\,s^{-1}}}\right)^{-\frac{1}{4}} \left(\frac{u_{\rm L}}{3.4\times10^{3}\,{\rm cm\,s^{-1}}}\right)^{-\frac{1}{4}} \\
&\left(\frac{\Delta W_{\rm ion}}{15.4\,{\rm eV}}\right)^{\frac{1}{2}} \left(\frac{T}{1.7\times10^{2}\,{\rm K}}\right)^{-\frac{1}{2}},
\end{aligned}
\tag{124}
$$

$$
\begin{aligned}
\eta^{(cd)} = 3.3\times10^{2} &\left(\frac{\Delta q_{\rm A,C}}{6.2\times10^{2}\,{\rm e}}\right)^{-\frac{1}{2}} \left(\frac{n_{\rm g}}{4.7\times10^{13}\,{\rm cm^{-3}}}\right)^{\frac{1}{2}} \\
&\left(\frac{n_{\rm S}^{\bowtie}}{8.8\times10^{-1}\,{\rm cm^{-3}}}\right)^{-\frac{1}{2}} \left(\frac{n_{\rm L}^{\bowtie}}{4.0\times10^{-14}\,{\rm cm^{-3}}}\right)^{-\frac{1}{2}} \\
&\left(\frac{r_{\rm S}}{1.0\times10^{-4}\,{\rm cm}}\right)^{-\frac{1}{2}} \left(\frac{r_{\rm L}}{1.0\,{\rm cm}}\right)^{-\frac{1}{2}} \\
&\left(\frac{\zeta}{1.0\times10^{-18}\,{\rm s^{-1}}}\right)^{\frac{1}{2}} \\
&\left(\frac{\Delta v_{\rm L,S}}{3.4\times10^{3}\,{\rm cm\,s^{-1}}}\right)^{-\frac{1}{2}},
\end{aligned}
\tag{125}
$$

$$
\begin{aligned}
\eta^{\rm (d)}_{\rm crit} = 5.9\times10^{1} &\left(\frac{\Delta q_{\rm A,C}}{6.2\times10^{2}\,{\rm e}}\right)^{-\frac{1}{2}} \left(\frac{n_{\rm g}}{4.7\times10^{13}\,{\rm cm^{-3}}}\right)^{\frac{1}{2}} \\
&\left(\frac{n_{\rm S}^{\bowtie}}{8.8\times10^{-1}\,{\rm cm^{-3}}}\right)^{-1} \\
&\left(\frac{r_{\rm S}}{1.0\times10^{-4}\,{\rm cm}}\right)^{-\frac{3}{2}} \left(\frac{r_{\rm L}}{1.0\,{\rm cm}}\right)^{\frac{1}{2}} \\
&\left(\frac{\zeta}{1.0\times10^{-18}\,{\rm s^{-1}}}\right)^{\frac{1}{2}} \left(\frac{u_{\rm L}}{3.4\times10^{3}\,{\rm cm\,s^{-1}}}\right)^{-\frac{1}{2}} \\
&\left(\frac{\Delta W_{\rm ion}}{15.4\,{\rm eV}}\right)^{\frac{1}{2}} \left(\frac{T}{1.7\times10^{2}\,{\rm K}}\right)^{-\frac{1}{2}}.
\end{aligned}
\tag{126}
$$

Conclusions of Muranushi 2010

- Ice dust-dust collisional charging is considered, fluffiness of the dust aggregates, regions with higher dust number density than that of MMSN.

1. As dust number density N increase, the dust plasma experience four phase.

- The latter two phases are common, where dust-dust collisional charging <u>needs</u> to be taken into account.

2. For typical fluffy dust, the lightning strikes at $N_{\mathrm{crit}} = 10 \sim 100$. $N = 100$ is plausible when dust sedimentation or streaming instability takes place.

- It is <u>possible</u> that lightning do take place.
- We have an analytic solution of $N_{\mathrm{crit}}(r_{\mathrm{S}}, r_{\mathrm{L}}, D_{\mathrm{S}}, D_{\mathrm{L}})$ for use in other disk environment.

-- Planned end of my talk --

Thank you for your attentions!!

Part X-1
An exercise

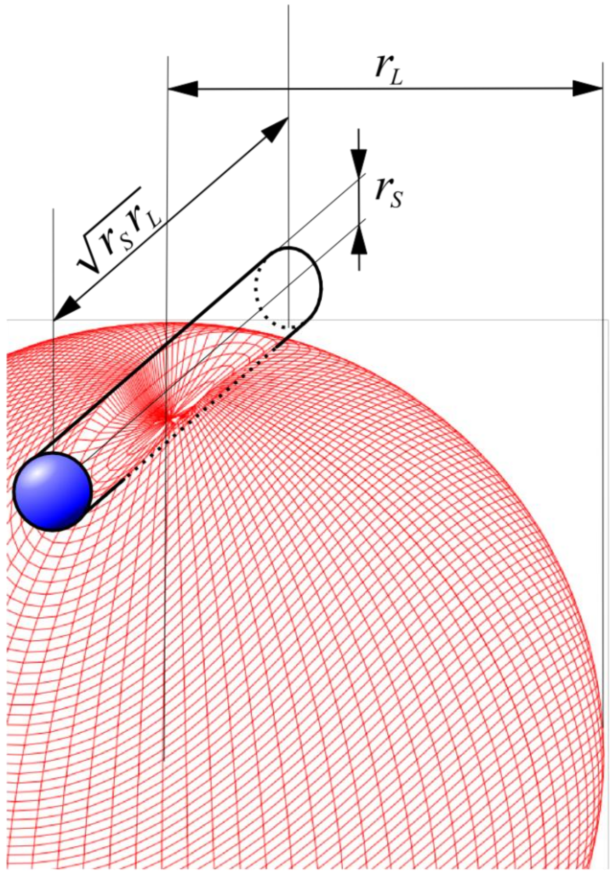
An estimation for N_{crit}

MMSN, r = 2.7AU, Gas : S : L = 1: $10^{-2} N$:$10^{-3} N$

Let us consider the following pair of dust:

Monomer Size : $r_{\mathrm{m}} = 10^{-5}$ cm

$D_{\mathrm{S}} = 2.0$	$D_{\mathrm{L}} = 2.4$
$r_{\mathrm{S}} = 10^{-2}$ cm	$r_{\mathrm{L}} = 10^{2}$ cm
$m_{\mathrm{S}} = 3.9 \times 10^{-9}$ g	$m_{\mathrm{L}} = 1.5 \times 10^{2}$ g
$n_{\mathrm{S}} = 4.0 \times 10^{-2} \times \eta$ cm^{-3}	$n_{\mathrm{L}} = 1.0 \times 10^{-15} \times \eta$ cm^{-3}



Grazing cross section :

$\sigma_{\mathrm{SL}} = r_{\mathrm{S}}\, r_{\mathrm{L}} = 1.0$ cm^2

relative velocity = icebreaking velocity :

$v_{\mathrm{SL}} = 3.4 \times 10^{3}$ cm/s (Wada et al.2008)

Grazing collision event rate:

$\sigma_{\mathrm{SL}}\, n_{\mathrm{S}}\, n_{\mathrm{L}}\, v_{\mathrm{SL}} = 1.4 \times 10^{-13}\ N^{2}$ [cm^{-3} s^{-1}]

ice surface density : $\sigma_{ch} = 6.2 \times 10^9$ e cm^{-2}

charge separation efficiency : $N_{ch} = 10^{-1}$

(e.g. Dash et.al. 2001)

Contact cross section is smaller of :

- $S_{kiss} = r_S^{3/2} r_L^{1/2}$ dense kiss
- $S_{kiss} = r_m^{2-DL} r_S^{5/2} r_L^{DL-5/2}$ sparse kiss

This case is sparse kiss:

$S_{kiss} = 6.3 \times 10^{-4}$ cm^{-2}

charge separation per collision event :

$\triangle q = \sigma_{ch} N_{ch} S_{kiss} = 4.0 \times 10^5$ e

charge separation rate :

$J_{SL} = \triangle q\, \sigma_{SL}\, n_S\, n_L\, v_{SL} = 5.5 \times 10^{-8}\ N^2$ e cm^{-3} s^{-1}

$J_{ie} = e\, \zeta\, n_g = 4.7 \times 10^{-5}$ e cm^{-3} s^{-1}

lightning critical point :

$J_{SL} = J_{ie} \quad \therefore N_{crit} = 29$

fluffiness of dust

multi-component dust

dust denser than MMSN

are all important for lightning

Part X-2
Answers(?) to the problems

Answers to Three Problems against Chondrule Formation by Lightning

①Neutralization Problem (Gibbard ,Levy & Morfill 1997)

- Lightning do not occur. Since PPD is weakly ionized and conductive, and dust is few, generated E field is too weak. $E \propto n^2$ so you need unnaturally high dust number density.

②Energetics Problem (e.g. Weidenschilling 1997)

- If lightning do occur, it isn’t energetic enough to melt all the chondrules observed today, because the budget is turbulent energy --- a little portion of total kinetic energy.

③Destruction Problem (Güttler+ 2008)

- If lightning do occur, experiments show that it destroys the dust aggregates rather than melts them.

①Neutralization Problem (Gibbard ,Levy & Morfill 1997)

- Lightning do not occur. Since PPD is weakly ionized and conductive, and dust is few, generated E field is too weak. $E \propto n^2$ so you need unnaturally high dust number density.

A1. If dust aggregates are fluffy, you need much less dust. Moreover, E grows steeper than N^2

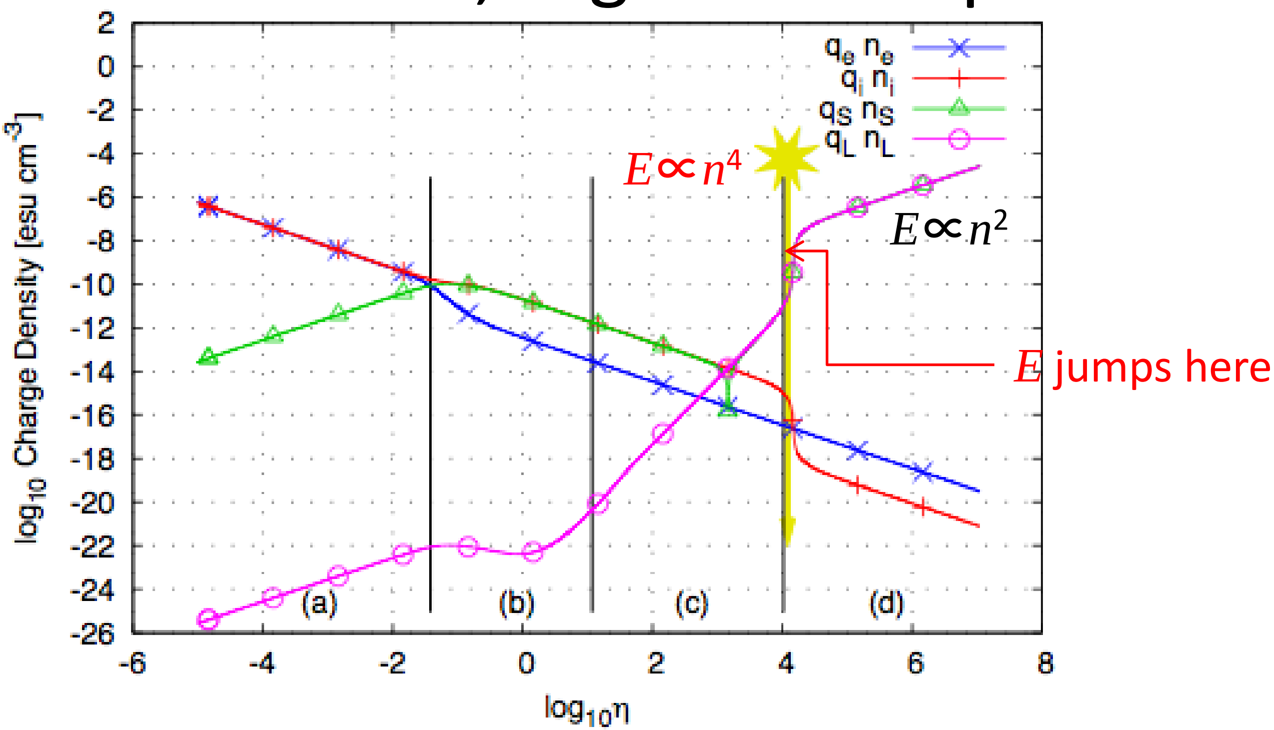
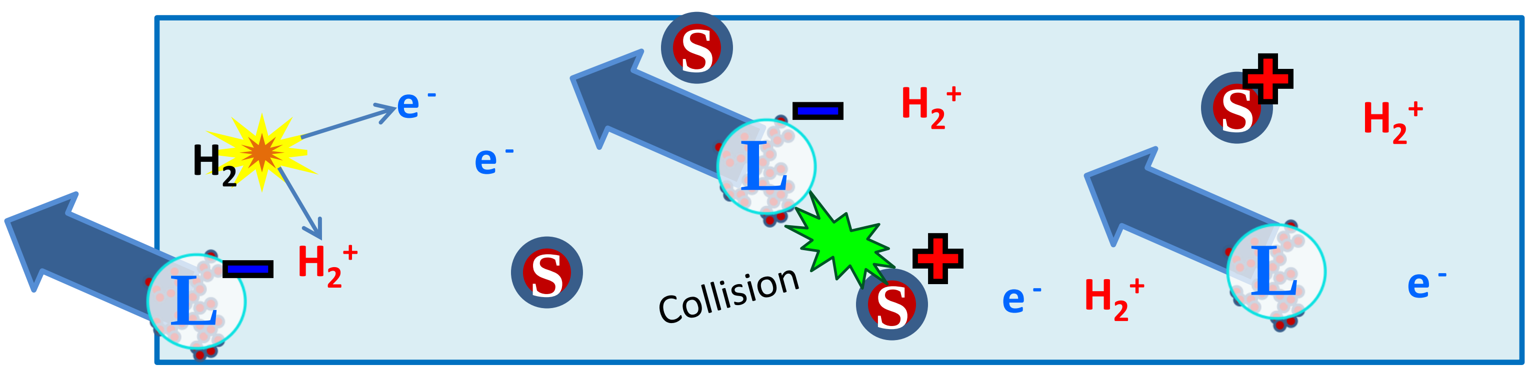


Figure 3. Amount of charge stored in each species, en_e, en_i, $|q_S|n_S$, and $|q_L|n_L$, as function of η. This figure is for ice dust-

②Energetics Problem (e.g. Weidenschilling 1997)

- If lightning do occur, it isn't energetic enough to melt all the chondrules observed today, because the budget is turbulent energy --- a little portion of total kinetic energy.

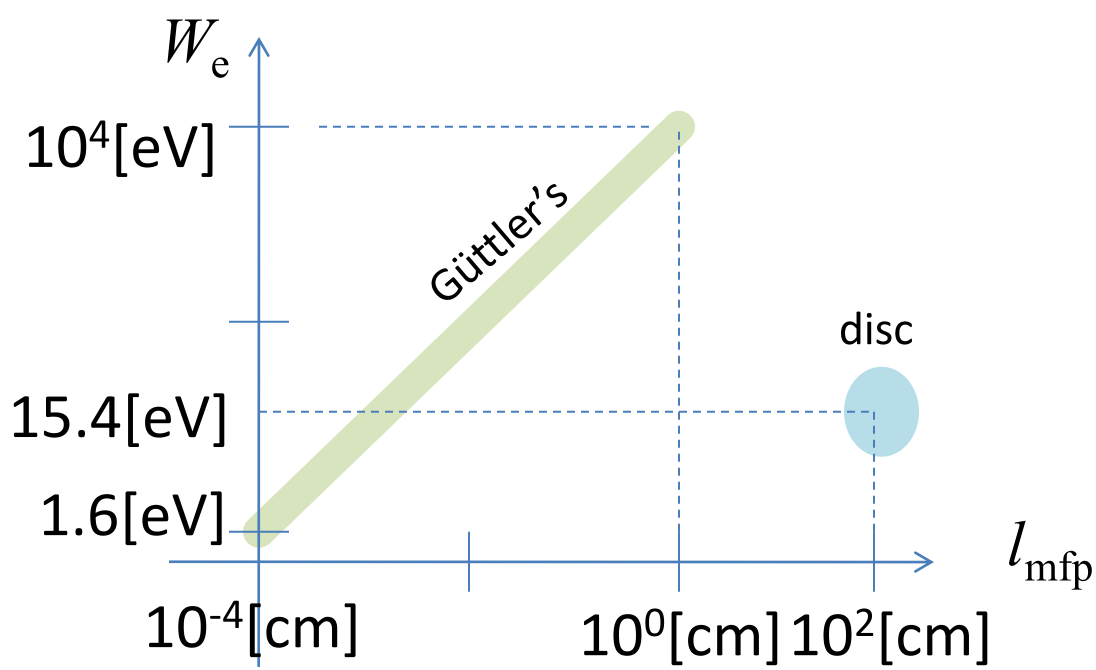
A2. Not only turbulent energy, but whole the dust migration energy, may be harnessed by the *E* field and converted to lightning, for certain choices of dust parameters.



③Destruction Problem (Güttler+ 2008)

- If lightning do occur, experiments show that it destroys the dust aggregates rather than melts them.

A3. Lightning environment in protoplanetary disc is different from that used in the experiment (Güttler+ 2008.) I don't know if two has the same effect on dust aggregates.



$$W_e = e\,E\,l_{mfp}$$

New Problem I’ve Learned in this workshop

- Chondrule forming environment is considered to be reductive, rather than oxidative
- H_2O environment = oxidative.
- A con for ice-dust induced lightning as a heating mechanism for chondrule.

Part X-3
Observation

Lightning Mechanism is Too Uncertain

… in spite of that, you can estimate typical luminosity or duration of an lightning event fairly well.

mean free path : $l = 1.2 \times 10^2$[cm]

ionization energy : $eE\,l = 15.4$eV

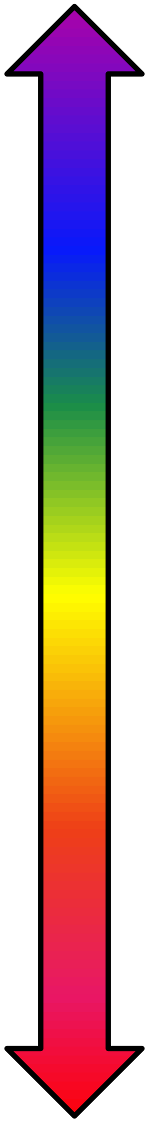
critical field strength: $E = 4.3 \times 10^{-4}$[G]

disk scaleheight : $H = 2.4 \times 10^{12}$[cm]

lightning energy per event: $E^2/8\pi \times H^3$

$= 4.3 \times 10^{29}$[erg]

Possible signals of disc lightning

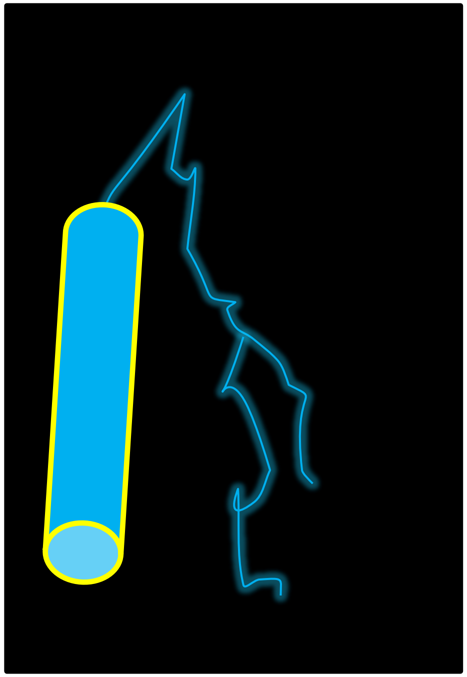


- γ-ray: 3×10^{11} eV
  - Recently, it has been revealed that thunderclouds and lightning discharges may produce relativistic electrons and gamma-rays(～10MeV). (Enoto et al. 2008)
- UV lines
  - Recombination lines from ionized molecules

    $$H_2^+ + e^- \rightarrow H_2 + 15.4\mathrm{eV}$$
  - Obstacles: interstellar dust absorption
- Optical (Literally see the Lightning)
- IR imaging
  - Disc heating by lightning. If you want to distinguish from other sources, see variability/timing/correlation.
- ALF wave: wavelength ～0.1AU
  - Earth thunderclouds emit ELF wave of its scale height (e.g.Koshak & Krider 1989)

Shape of a lightning bolt

- Terrestrial lightning bolts are known to have radii of ～5000 mfp. Borrowing this, astrophysical lightning is a cylinder:
  - length H = 2.4×10^{12}[cm]
  - radius 5000l = 6×10^{5}[cm]
  - filled with 15.4eV electrons
  - amount to 4.3×10^{29}[erg]
  - duration 10^{4}[sec]
  - Energy Budget tells minimum interval: 10[sec]
- How can we observe this object?



Basic Energetics

$$\frac{4.3 \times 10^{29}[\mathrm{erg}] \quad 10^{23}}{10^{4}[\mathrm{sec}] \quad (100\mathrm{pc})^{2} \;\; 300\mathrm{GHz}} = 1.4\mathrm{Jy}$$

- ALMA: 0.1mJy is available.
- Default band for lightning is UV, which is very hard to observe.
- Is there any mechanism to transfer a portion of the lightning energy to other bands?

Candidates

- Cyclotron radiation
- Planck radiation Tail
- Velocity dispersion of charged molecules
- Strange molecules formed by lightning
- Noise mining (nongaußianity)
- afterglow

Electron Cyclotron Radiation

$$\omega = eB/mc$$

- Typical MRI disk → B = 6[G] → 0.1GHz
- ALMA bands: 31.3GHz~950GHz
- Lightning equipartition magnetic field : 3500[G] → 50GHz
- Lightning leaders (charge packets at the front of lightning bolts) may cause more magnetic field?

Colder Tail of Planck Radiation

- If the lightning bolt cylinder is heated by electrons and cooled by Blackbody radiation, equilibrium T = 800K
- Looking at the cylinder @900GHz band

$\sim 10^{20}$[erg/s] → 3μJy

Velocity dispersion of charged molecules

- +1, -1 charged molecular species are also accelerated by lightning field. The acceleration and mean free paths are the same as electron, so the energy is: 15.4eV
- molecular weight 30 = 7km/s
- A velocity much greater than thermal speed is a smoking gun for an acceleration process.

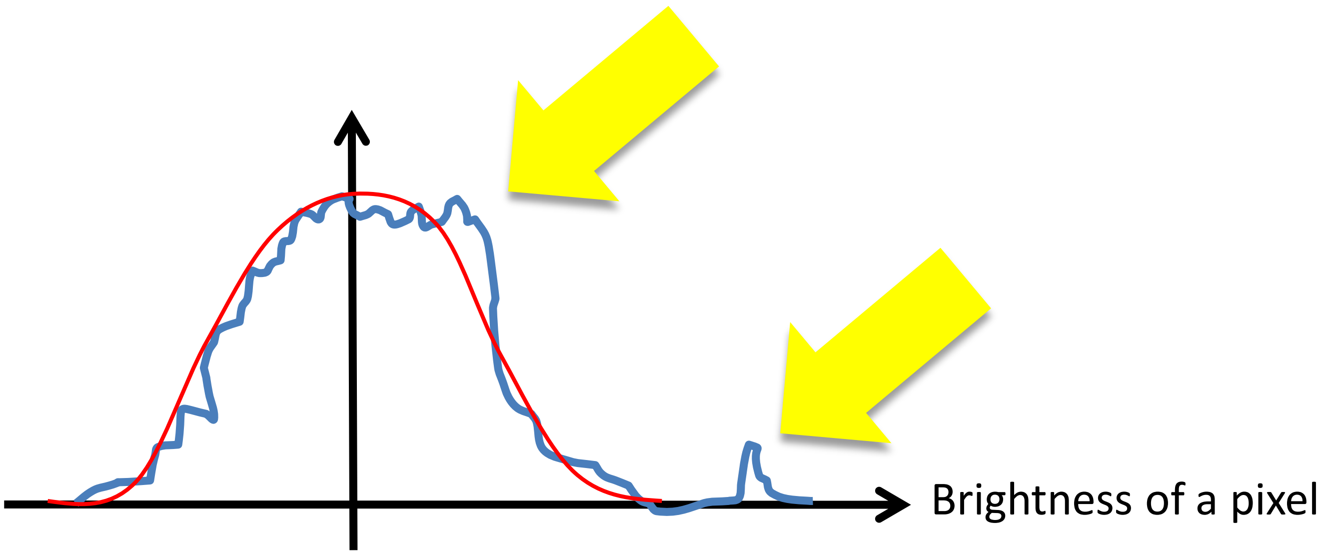
Strange molecules formed by lightning

- Which molecules? Das wußte ich doch nicht.
- Dust struck by lightning?
- Amino acid?

→ protoplanetary disk = origin of life hypothesis

nongaußianity

- Draw information from protoplanetary disks imaging
- statistically detect that there are transient, bright spots in disks, of timescale ~1hr



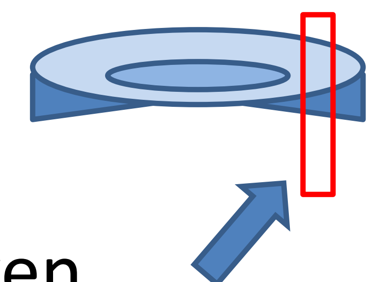
afterglow

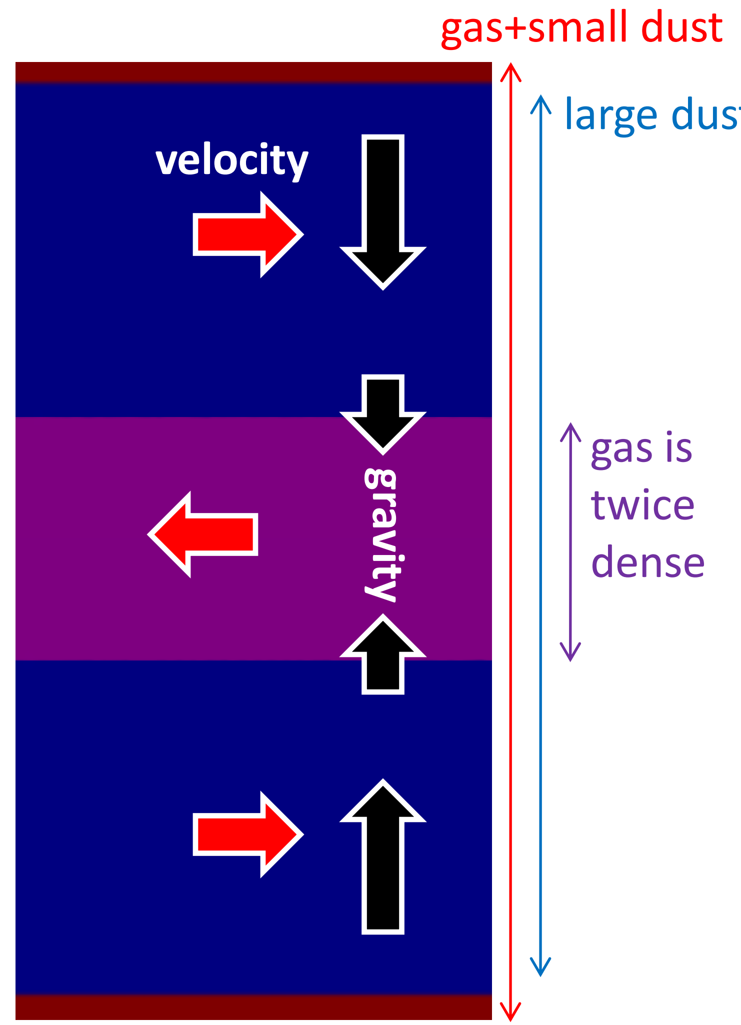
- afterglow of lightning

Part X-4
About the opening movie

Initial Conditions

- 2-D model
- *φ-z* slice of the disk
- gas+small dust（red）, large dust（blue）
- gravity towards equatorial plane
- velocity shear given to cause KH instability (shear velocity is not self-maintained…)





Resistive MHD with advected scalars

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \bullet \left(\rho \mathbf{u}\overleftarrow{\mathbf{u}} - \mathbf{B}\overleftarrow{\mathbf{B}}\right) + \nabla P^* = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0$$

$$\frac{\partial E}{\partial t} + \nabla \bullet \left(\left(E + P^*\right)\mathbf{u} - \mathbf{B}(\mathbf{B} \bullet \mathbf{u})\right) = 0$$

$$\frac{\partial S_i}{\partial t} + \nabla \bullet (S_i \mathbf{u}) = 0$$

Independent Variables

density ρ, velocity $\mathbf{u}$,
magnetique field **B**, total energy *E*
scalar fields S[i]

Constraint

$$\nabla \bullet \mathbf{B} = 0$$

Dependent Variables

current $\mathbf{j} = \nabla \times \mathbf{B}$

electric field $\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{j}$

Internal Energy

$$\varepsilon = E - \tfrac{1}{2}\rho u^2 - \tfrac{1}{2}B^2$$

Gas pressure $P = (\gamma - 1)\varepsilon$

Total Pressure $P^* = P + \tfrac{1}{2}B^2$

2-Scalar Field Model

- S[0]… Number density of the Larger dust
- S[1]… Ionization degree

$$\frac{\partial S_0}{\partial t} + \nabla \bullet \left(S_0 \left(\mathbf{u} + \mathbf{u}_g(z) \right) \right) = 0$$

$$\frac{\partial S_1}{\partial t} + \nabla \bullet \left(S_1 \mathbf{u} - D_1 \nabla S_1 \right) + \frac{S_1 - S_{1,\mathrm{eq}}}{\tau_1} = \delta_{\mathrm{discharge}}$$

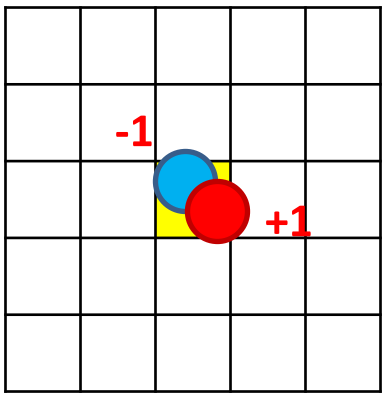
- Large dust advects while falling at the terminal velocity.
- Ionization suddenly rise at lightning path (discharge model; next slides.) then it advects, diffuses and rapidly decays to equilibrium value.

Discharge toy model

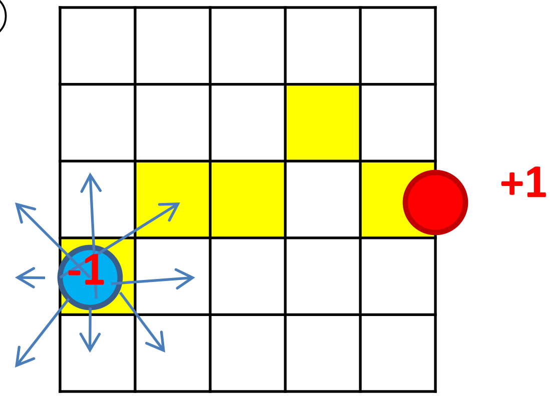
Solomon, Adamo, Baker 2002(discharge) & Muranushi(toy)

① $\mathbf{E}_{\mathrm{esf}} = \cancel{-\mathbf{u}\times\mathbf{B}} + \eta\mathbf{j} \longrightarrow \mathbf{E}_{\mathrm{esf}} \propto S_0^{\,4} S_1^{\,-1}\left(\mathbf{u}+\mathbf{u}_g\right)$

②



③



①Suppose the dust plasma is in (c)charge-up phase: Electric field is dominated by $\eta\mathbf{j}$ term.

②Introduce a pair of 'Charge Packet' (q = ±1) at the cell Eesf > Ecrit

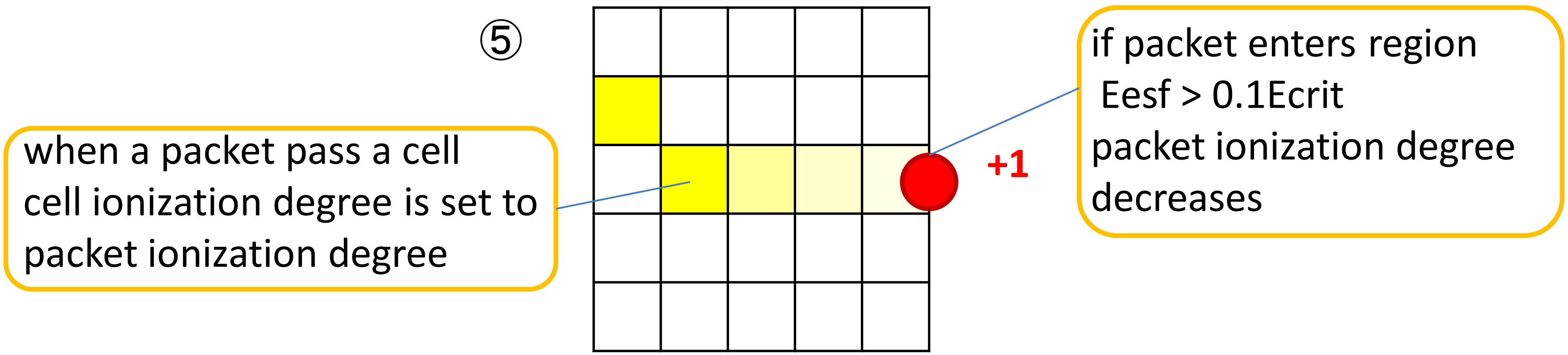
③Each charge packet randomwalk as a chess king. They obey electric field and likes the highly ionized cell.

The probability that direction **n** is chosen

$$P(\mathbf{n}) \propto \mathrm{expone}\left(q S_1^{\,0.5} \frac{\mathbf{n} \bullet \mathbf{E}_{\mathrm{esf}}}{\left|\mathbf{E}_{\mathrm{esf}}\right|} \right)$$

if x > 0
    expone(x) = x
else
    expone(x) = exp(x)

Discharge toy model



④ Initially, charge packet has ionization degree S[1] = 1.0

⑤ At each cell charge packet ionization is updated as

$$S_1 \leftarrow S_1 \min\left(1.0, \frac{|\mathbf{E}_{esf}|}{0.1 E_{crit}}\right)$$

charge packet can survive if Eesf > 0.1Ecrit

(not Eesf > Ecrit ;Avalanche discharge model)

⑥ If the packet ionization degree < cell ionization degree, remove the packet

⑦ This happens in a instant (compared to hydro timescales)