Effects of Settling and Growth of Dust Particles on the Ionization by Radionuclides

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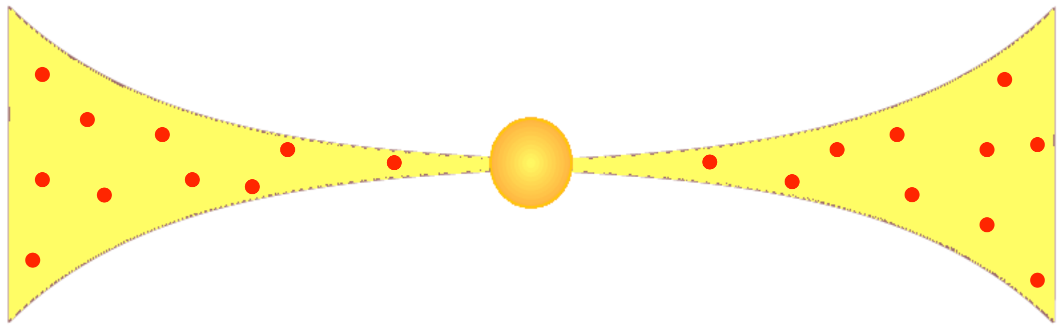
1. はじめに

原始惑星系ガス円盤における荷電状態

- MRI (Magnetorotational Instability)
- 化学進化 --- 物質の存在形態
- ダストの沈殿，成長 => 微惑星の形成

いままで扱われていなかった問題

- ダストの沈殿，成長
  - 放射性元素によるガスの電離率
- UV，Xの影響
  - ダストの荷電状態に対する光電効果の影響



Long–lived nuclides

Table. 1:

The Ionization Rates of a Hydrogen Molecules, $\zeta_R^{H_2}(X)$, by the Major Long-Lived Radionuclides X with the Abundance $\chi(X)$ Relative to Hydrogen Nucleus by Number in the Primitive Solar Nebula.

Nuclide X	Decay Mode	$t_{1/2}(X)$ (yrs)	$E_{em}(X)$ (keV)	Abundance $\chi(X)$	$\zeta_R^{H_2}$ (s^{-1})
^{40}K		1.28×10^9		2.2×10^{-10}	1.1×10^{-22}
	β^- (89.3 %)		534		8.4×10^{-23}
	EC (10.7 %)		1461		2.8×10^{-23}
^{235}U	Ac series	7.04×10^8	44584	2.4×10^{-13}	1.6×10^{-23}
^{238}U	U series	4.47×10^9	47969	7.7×10^{-13}	8.5×10^{-24}

Note. The ionization rates of a helium atom are given by $\zeta_R^{He} \approx 0.84\zeta_R^{H_2}$.

Short–lived nuclides

Table. 2:

The Ionization Rates of a Hydrogen Molecules, $\zeta_R^{H_2}(Y: y_0)$, by the Short-Lived Radionuclides Y with the Abundance $\chi(Y: y_0)$ Relative to Hydrogen Nucleus by Number in the Primitive Solar Nebula.

Nuclided Y	Decay Mode	$t_{1/2}(Y)$ (yrs)	$E_{em}(Y)$ (keV)	Abundance $\chi(Y: y_0)$	$\zeta_R^{H_2}(Y: y_0)$ (s^{-1})
^{26}Al		7.4×10^5		$(1.8\text{-}2.5) \times 10^{-10}$	$(7.3\text{-}10) \times 10^{-19}$
	β^+ (82 %)		3304		$(6.5\text{-}9.1) \times 10^{-19}$
	EC (1.8%)		1978		$(8.5\text{-}12) \times 10^{-20}$
^{36}Cl		3.0×10^5		$6.4 \times 10^{-13}\text{-}2.6 \times 10^{-11}$	$6.4 \times 10^{-22}\text{-}2.5 \times 10^{20}$
	β^- (98.1 %)		272		$5.9 \times 10^{-22}\text{-}2.4 \times 10^{-20}$
	$\beta+$ (1.8 %)		1063		$4.5 \times 10^{-23}\text{-}1.8 \times 10^{-21}$
^{60}Fe	β^-	1.5×10^6	2741	$1.6 \times 10^{-11}\text{-}3.2 \times 10^{-11}$	$(3.0\text{-}5.9) \times 10^{-20}$

Note. The ionization rates of a helium atom are given by $\zeta_R^{He}(Y: y_0) \approx 0.84\zeta_R^{H_2}(Y: y_0)$.

2. ダスト粒子の沈澱･成長過程

原始太陽系円盤ガスに対する、放射性元素による電離作用と
ダスト粒子の成長･沈殿による電離度への影響の調査。

■ 放射性元素による原始太陽系円盤に対する電離率

$$\zeta_{\rm gas}(X) = w(X)\frac{n(X)}{n(H)}\frac{E_{\rm em}(X)}{W_{\rm gas}}$$

ダスト粒子の半径

ダスト粒子の密度分布

⇒ ダスト粒子の成長方程式を解く。

"Growth and Sedimentation of Dust Grains
in the Primodial Solar Nebula"
Nakagawa, Nakazawa & Hayashi (1981)

原始太陽系円盤ガスに対する、放射性元素による電離率とダスト粒子の成長・沈殿による電離率への影響の調査。

- ダスト粒子の成長・沈殿による電離率の影響とは？

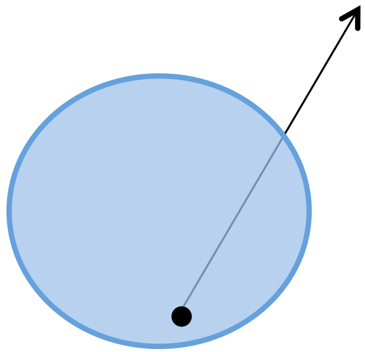
  放射性元素はダスト粒子内部に存在する

① ダスト粒子の沈殿による放射性元素の数の増加による電離率の増加

② 沈殿によるダスト粒子の数の増加による電離率の減少 （自己遮蔽）

③ ダスト粒子の成長による電離率の減少

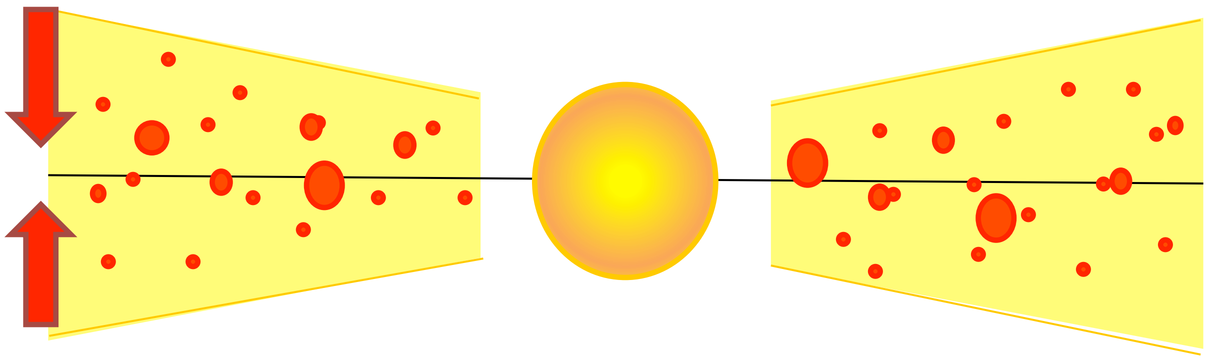
ダスト粒子内部で崩壊した放射性元素から
放出される粒子がダスト粒子内部を走ることに
よりその粒子がもつエネルギーが減少する。



● Ionization Rate for H_2 molecule

$$\zeta_{\mathrm{H_2}}(\mathrm{X};m,Z) = \frac{E_{\mathrm{em}}(\mathrm{X};m)}{W_{\mathrm{H_2}}} \frac{w(\mathrm{X})\chi(\mathrm{X};m,Z)}{\chi(\mathrm{H_2})+\chi(\mathrm{He})} \qquad \chi(\mathrm{X};m,Z) = \frac{n(\mathrm{X};m,Z)}{n(\mathrm{H})}$$

① By increasing (decreasing) the number of radionuclides.

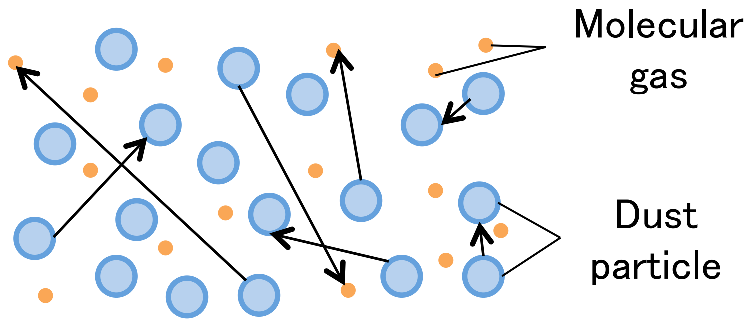


● Ionization Rate for H_2 molecule

$$\zeta_{H_2}(X;m,Z) = \frac{E_{em}(X;m)}{W_{H_2}} \frac{w(X)\chi(X;m,Z)}{\chi(H_2)+\chi(He)} \qquad \chi(X;m,Z) = \frac{n(X;m,Z)}{n(H)}$$

② by increasing the number of the dust particles.

The Emitted particles is absorbed by the dust particles (Self Shielding).



$$p_{gas} = \frac{\alpha_{gas}}{\alpha_{gas}+\alpha_{dust}} \sim \frac{\rho_{gas}}{\rho_{gas}+\rho_{dust}}$$

: incident probability to gas

(only rough approximation)

α : absorption coefficient

ρ : mass density

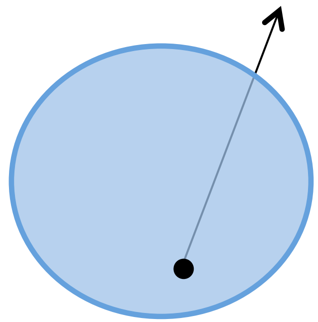
$$w(X) \Rightarrow p_{gas} w(X)$$

- **Ionization Rate for H_2 molecule**

$$\zeta_{H_2}(X; m, Z) = \frac{E_{em}(X; m)}{W_{H_2}} \frac{w(X)\chi(X; m, Z)}{\chi(H_2) + \chi(He)} \qquad \chi(X; m, Z) = \frac{n(X; m, Z)}{n(H)}$$

③ by growing dust particles.

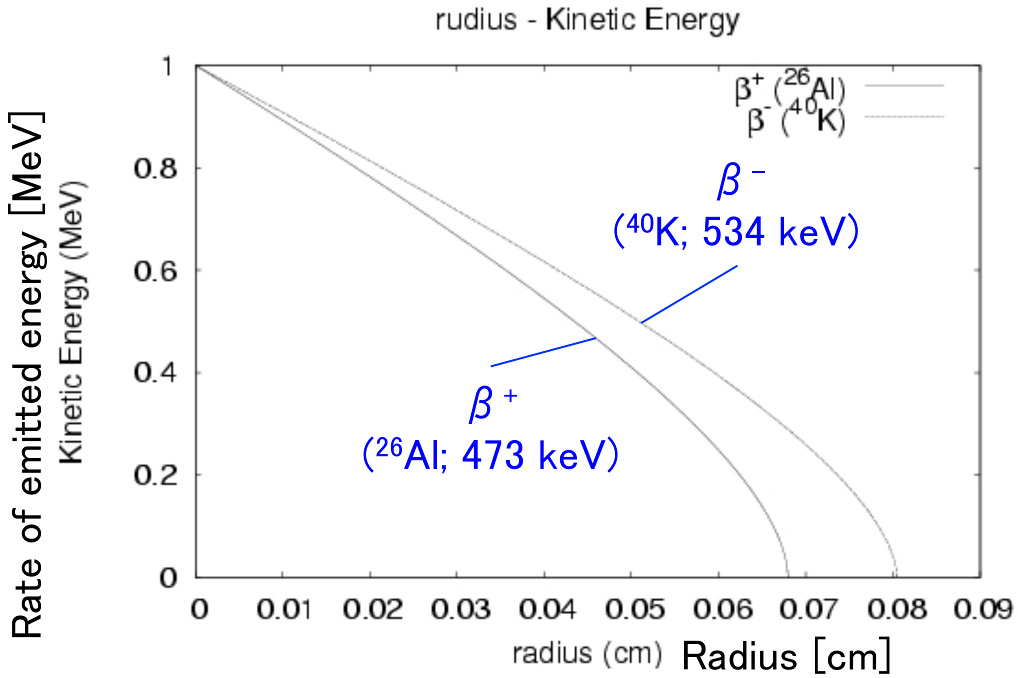
The energy of the emitted particles from the radionuclides is attenuated on passing through the dust particles.



- β −particle

We refer to the data of the stopping power and range tables for electrons in the paper of Berger et al (1993).

β −particles are completely Shielded by the dust radius with more than 0.1cm.

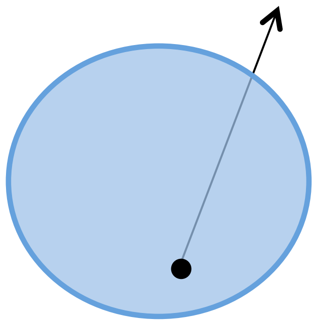


- Ionization Rate for H_2 molecule

$$\zeta_{\mathrm{H_2}}(\mathrm{X};m,Z) = \frac{E_{\mathrm{em}}(\mathrm{X};m)}{W_{\mathrm{H_2}}} \frac{w(\mathrm{X})\chi(\mathrm{X};m,Z)}{\chi(\mathrm{H_2})+\chi(\mathrm{He})} \qquad \chi(\mathrm{X};m,Z) = \frac{n(\mathrm{X};m,Z)}{n(\mathrm{H})}$$

③ Decreasing Ionization rates by growing dust particles.

The energy of the emitted particles from the radionuclides is attenuated on passing through the dust particles.



- γ −particle

$$E_{\mathrm{em}}(\mathrm{X};m) = E_{\mathrm{em}}(\mathrm{X}) \exp\left(-\frac{\langle x_{\mathrm{path}}\rangle}{\lambda_\gamma}\right)$$

75–90 % of energy of the gamma particles is emitted from the surface of the dust particles with the radius 1cm.

$\langle x_{\mathrm{path}}\rangle$: Mean Path of γ −particles through Dust Grain

$$\lambda_\gamma = \left(\frac{\mu}{\rho}\right)^{-1}$$

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i$$: photon mass attenuation coefficient

(Hubble and Seltzer, 1995)

■ Results of Growth and Settling of the dust particles (at $R = 1\ \mathrm{AU}$

Dust particles grow as time passes.

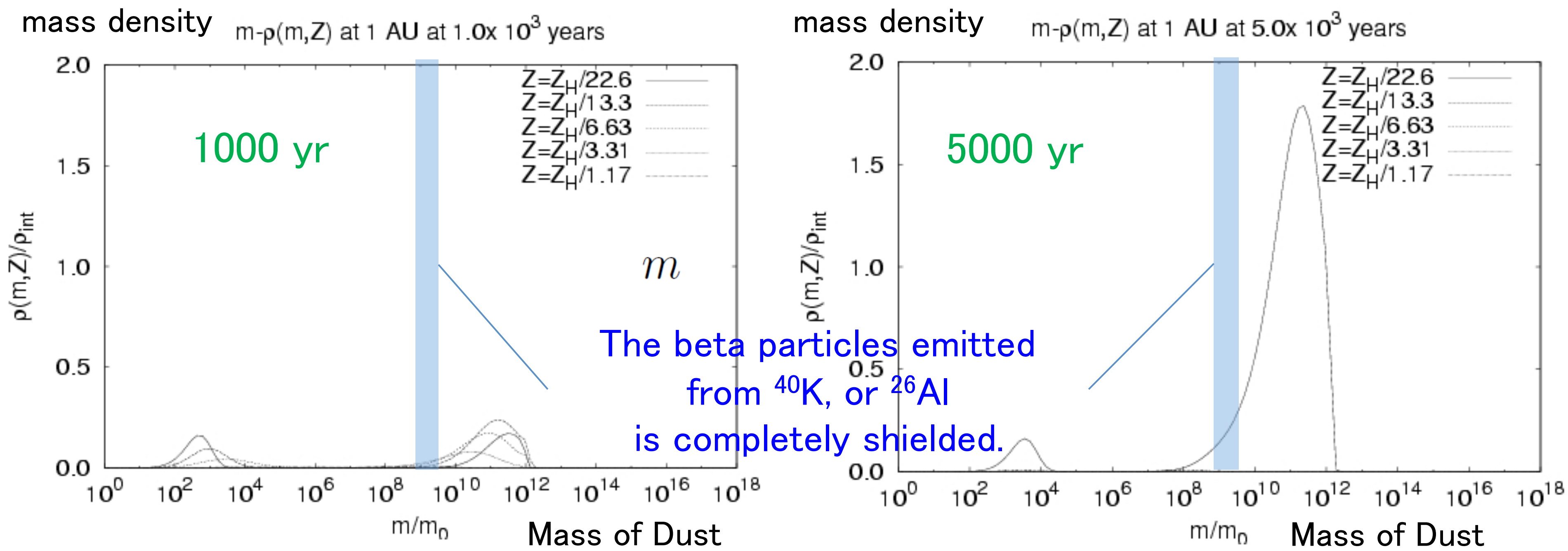
The most of emitted beta particles is shielded about 5000 years later.

$$\rho_{\mathrm{int}} = 3.54\ \mathrm{g\ cm^{-3}}$$
$$m_0 = 4.18 \times 10^{-12}\ \mathrm{g}$$

$\rho(m, Z)$: mass density of the dust particles.

m : mass of the dust particle.

Z : height from the midplane



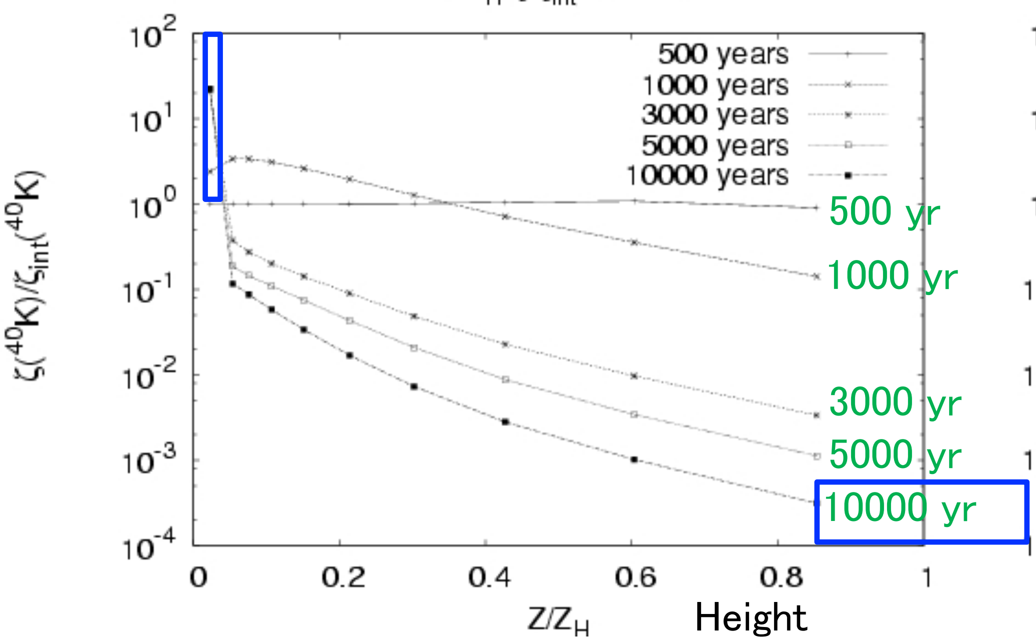
■ Results of Ionization Rate (at $R = 1\ \mathrm{AU}$

● ^{40}K (Long−Lived Radionuclide) $\zeta_{\rm int}(^{40}\mathrm{K}) = 1.1 \times 10^{-22}$

- About 20% of the energy is used for ionization, taking into account the effects of ②, and ③.

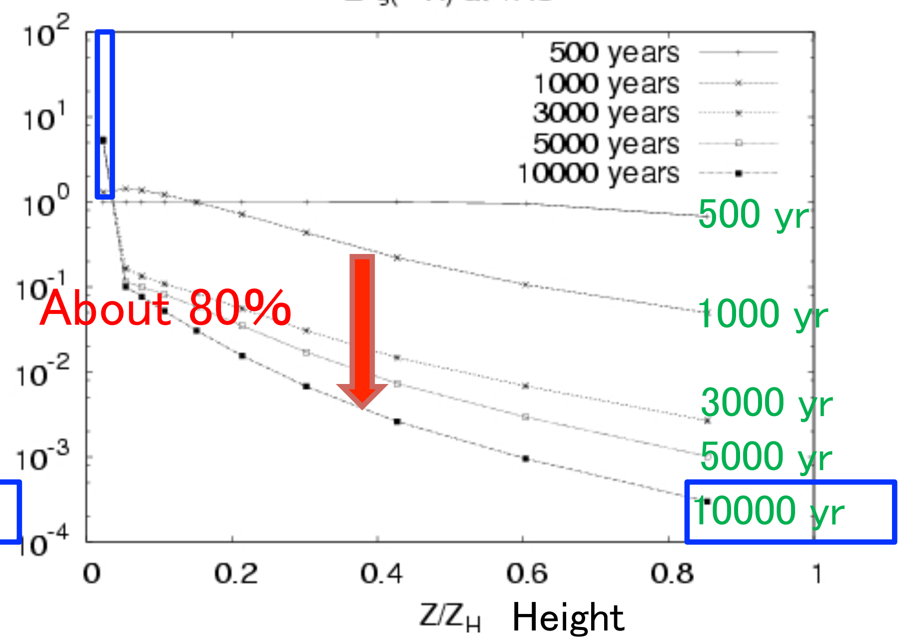
①

Ionization Rate



① + ② + ③

Ionization Rate



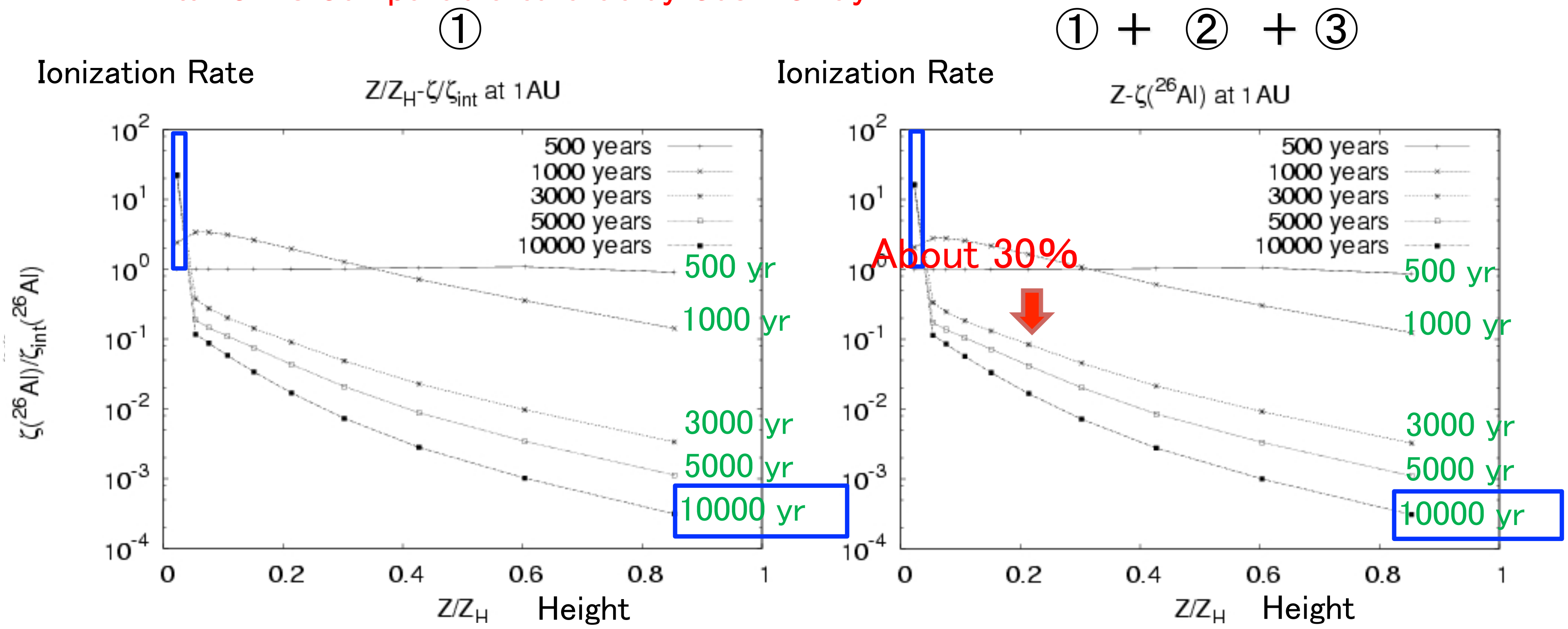
● Effect of Growing and Settling of Dust Particles on Ionization Rates

① By increasing the number of radionuclides.

② By increasing the number of dust particles (Self Shielding).

③ By Growing dust particles.

- ^{26}Al (Short-Lived Radionuclide) $\zeta_{\rm int}(^{26}\mathrm{Al}) = (7.3\text{-}10) \times 10^{-19}$
  - About 70% of the energy is used for ionization, taking into account the effects of ②, and ③.
  - Ionization Rates by ^{26}Al become more than 10 times by initial value; which is comparable to that by cosmic ray.



- Effect of Growing and Settling of Dust Particles on Ionization Rates
  ① By increasing the number of radionuclides.
  ② By increasing the number of dust particles (Self Shielding).
  ③ By Growing dust particles.

■ Summary of the Results

- About 20% of the energy used for Ionization by ^{40}K is effective at 1 AU.(Ionization by beta-particles is dominant.)
- About 70% of the energy used for Ionization by ^{26}Al is effective at 1 AU. (Ionization by gamma-particles is dominant.)

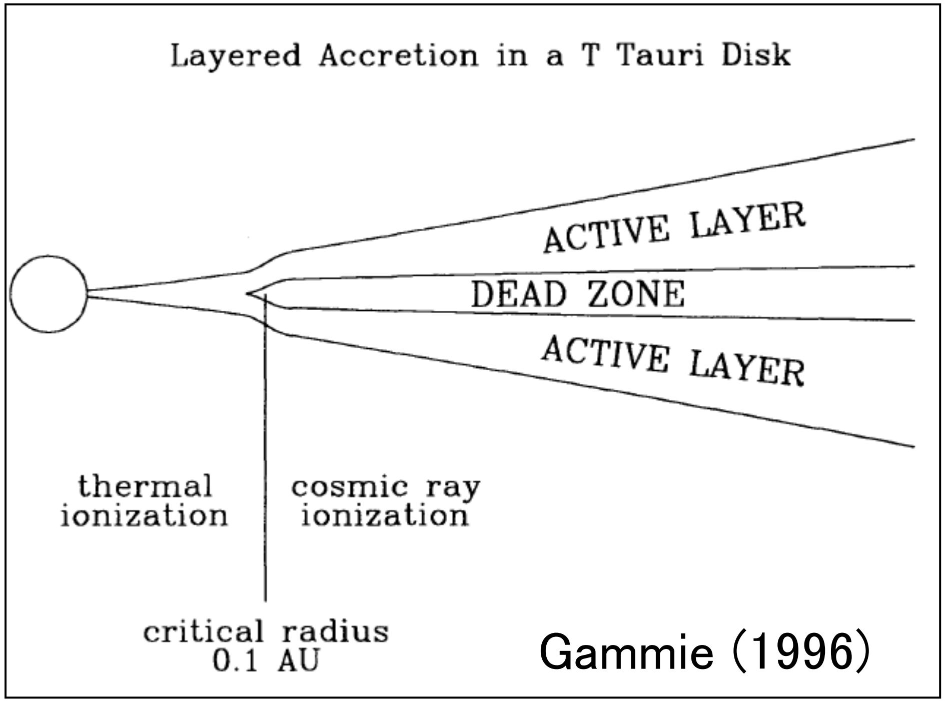
⇨

- About 70% of the all energy used for Ionization is effective at 1AU, taking into account the effect of ①, ②, ③.
- Ionization Rate by Radionuclides is comparable to that by cosmic ray around the midplane at 1AU.

⇨ Around midplane inner region
angular momentum transport by MRI is effective??

- Effect of Growing and Settling of Dust Particles on Ionization Rates
  - ① By increasing the number of radionuclides.
  - ② By increasing the number of dust particles (Self Shielding).
  - ③ By Growing dust particles.

- Ionization Rates, talking into account the other radionuclides?
- More accurate incident probability to gas?
- The other disk models?
- The other sedimentation models?
  - Sticking probability
- The other dust models?
  - paucity
- Abundance of Sort-Lived Radionuclides?
- MRI region?



- Effect of Growing and Settling of Dust Particles on Ionization Rates

① Increasing the ionization rates by increasing the number of radionuclides.

② Decreasing the Ionization rates by increasing the number of dust particles.

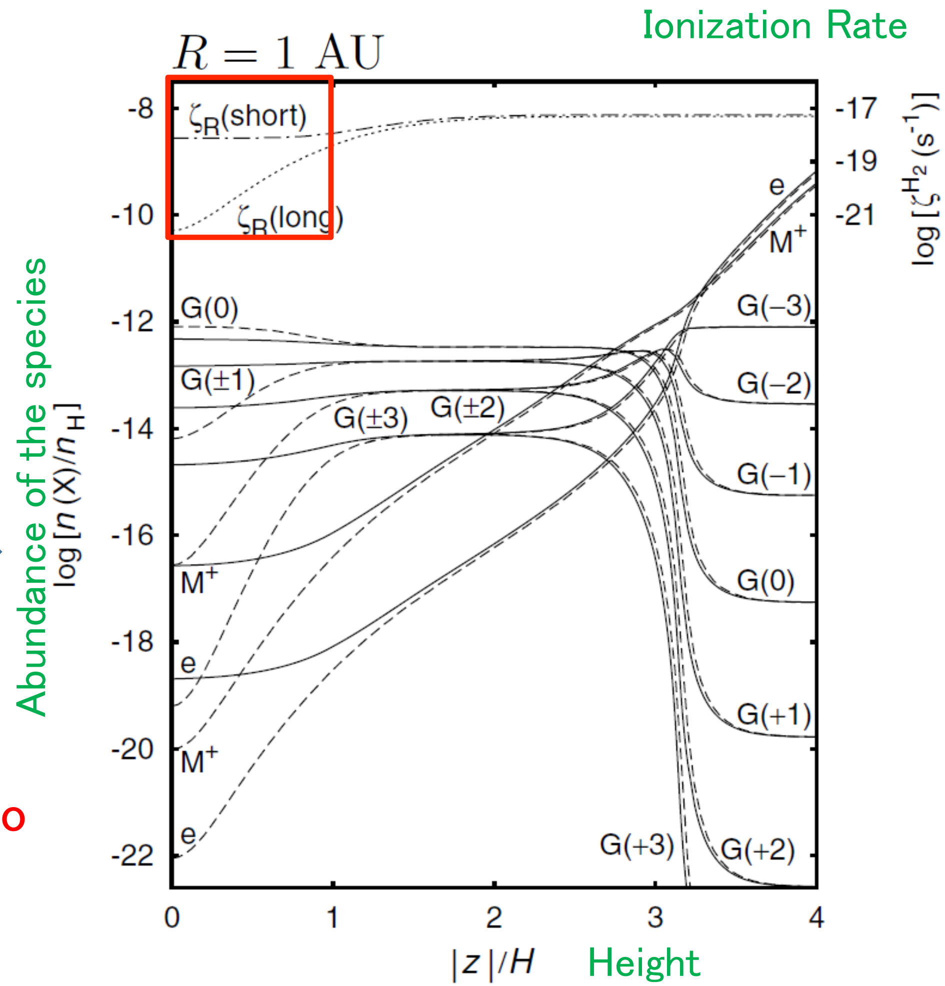
③ Decreasing Ionization rates by growing dust particles.

■ Umebayashi and Nakano (2009)

They investigated the ionization rate by radionuclides with newest data on abundance of the nuclides for the primitive solar nebula.

Not considering growth and sedimentation of dust particles.

Abundances of various species and ionization rate, as function of the height |Z| at the Earth's orbit ($R = 1$ AU



We investigate how ionization rates change around midplane, taking into account the effects of growth and settling of the dust particles?

■ Growth and Sedimentation of Dust particle

"Growth and Sedimentation of Dust Grains in the Primodial Solar Nebula"

Nakagawa, Nakazawa & Hayashi (1981)

- Sedimentation of Dust Grains

$$\frac{dv_Z}{dt} = -\frac{\rho_{\rm gas}}{\rho_{\rm mat}}\frac{C_{\rm th}}{r}v_Z - \frac{GM_\odot}{R^3}Z. \qquad \text{(at } R = 1\ \mathrm{AU}$$

$$\Rightarrow \quad v_Z = -\frac{\rho_{\rm mat}}{\rho_{\rm gas}}\frac{r}{C_{\rm th}}\frac{GM_\odot}{R^3}Z$$

$$= -9.3\times10^{-3}\left(\frac{\rho_{\rm mat}}{3\ \mathrm{g\ cm^{-3}}}\right)\left(\frac{r}{1\ \mu\mathrm{m}}\right)\left(\frac{Z}{0.047\ \mathrm{AU}}\right)\ \mathrm{cm\ sec^{-1}}.$$

- Growth Equation

$$\frac{\partial}{\partial t}\rho(m,Z) + \frac{\partial}{\partial Z}\left[\rho(m,Z)v_Z(m,Z)\right]$$

$$= -m\rho(m,Z)\int_0^\infty \alpha(m,m')\rho(m',Z)dm' + \frac{1}{2}m\int_0^m \alpha(m-m',m')\rho(m-m',Z)\rho(m',Z)dm'.$$

$$\alpha(m,m') = \frac{1}{mm'}\langle\sigma v\rangle_{m,m'} \qquad \langle\sigma v\rangle_{m,m'} = \pi(r+r')^2(\Delta v_{\rm B} + \Delta v_{\rm s})p_s$$

$\Delta v_{\rm B}$: relative thermal Brown velocity

$\Delta v_{\rm s}$: relative sedimentation velocity

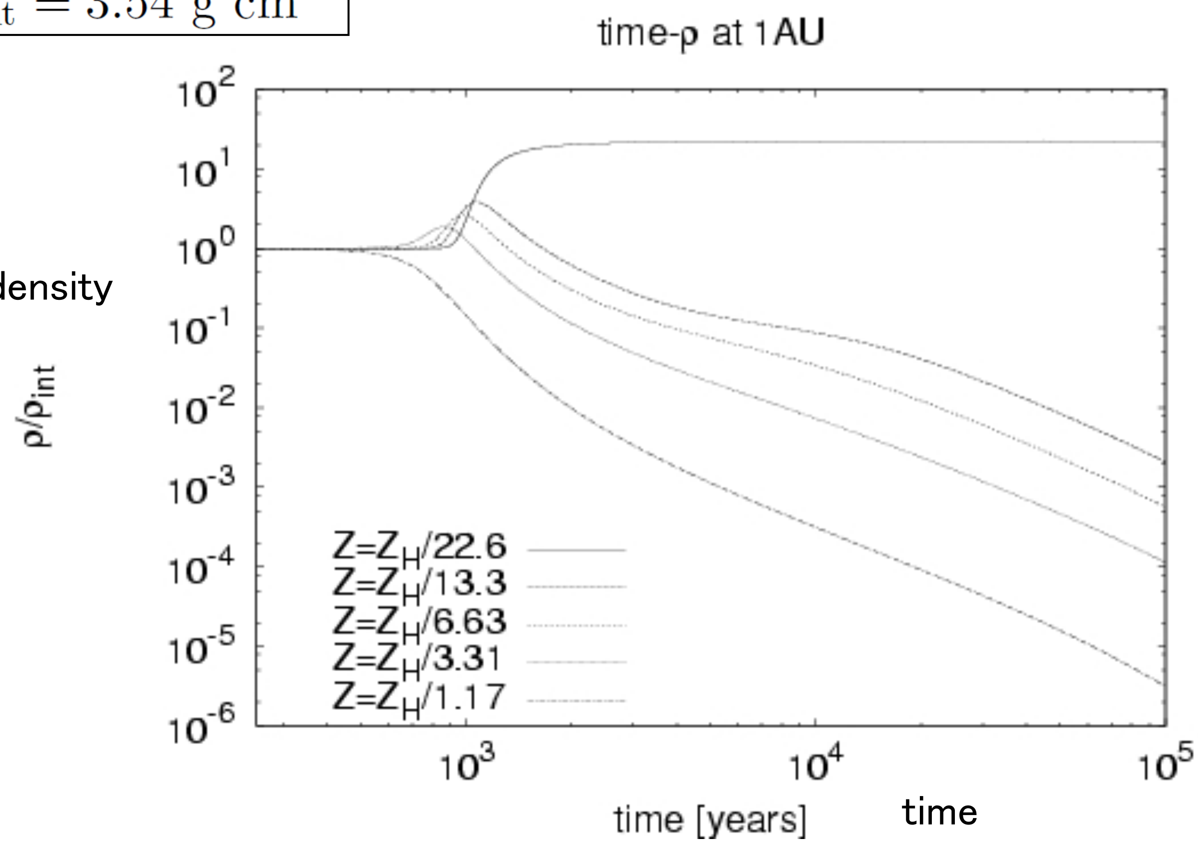
■ Results of Settling of the dust particles (at $R = 1\ \mathrm{AU}$

Dust particles settle to midplane as time passes.

Mass density around the midplane become dozens of times in some 1000 years.

$\rho_{\mathrm{int}} = 3.54\ \mathrm{g\ cm^{-3}}$

mass density



time

$Z=Z_H/45.2$

$Z=Z_H/13.3$

$Z=Z_H/6.63$

$Z=Z_H/3.31$

$Z=Z_H/1.17$