Interplay between dust and MHD turbulence in protoplanetary disks:
electric-field heating of plasmas and its effect on the ionization balance of dusty disks

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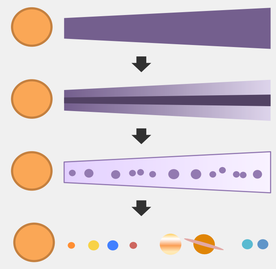
SUMMARY

The protoplanetary disks are thought to be turbulent by Magnetorotational instability (MRI) . The activity of MRI depends largely on the ionization degree of the gas, which depends on amount of dust grains that efficiently capture plasmas. Recent study pointed out that electric fields driven by MRI turbulence can significantly heat up electrons, which had been assumed to be negligible in previous study, and change the ionization balance of the disks. We focus on dust capturing and investigate how this affects the ionization degree. We have studied how this effect limits the saturation level of MRI turbulence in protoplanetary disks. For a minimum-mass solar nebula with the grain radius of 0.1μm and dust-to-gas mass ratio of 0.01, we find that the saturation level of MRI turbulence is significantly lowered inside 70 AU from the central star.

INTRODUCTION

Dust Evolution in Protoplanetary Disks

Protoplanetary Disks : The birth place of planets.
Small solids in solar system are made from dust grains in the disk. But, disk turbulence prevents planet formation. (e.g. blowing off dust layer)



➡ **To determine turbulent state of the disk is important !**

How does Turbulence occur in Disk?

Magnetorotaitonal instability (MRI) is the most reasonable mechanism.

Mechanism: Rotational shear of ionized disk stretches magnetic lines and angular momentum of disk is transported outside continuously by the stretched lines.

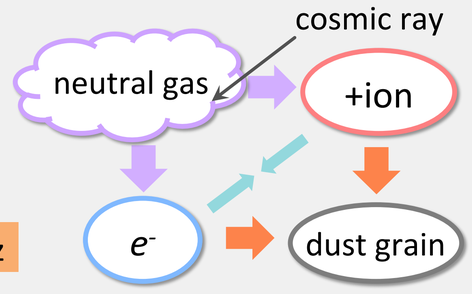
MRI conditions
1. **enough ionization degree**
2. magnetic fields penetrate through disk
3. differentially rotation disk

2 & 3 is basically satisfied in the disk.
1 is satisfied ➡ MRI drives turbulence.
1 is NOT satisfied ➡ MRI can't drive turbulence.

How is Ionization Degree determined in Disk ?

➡ Ionization balance

GAIN Cosmic ray ionizes neutral gas
LOSS Electrons recombine with +ions in gas
LOSS Dust grains capture electrons and +ionsz

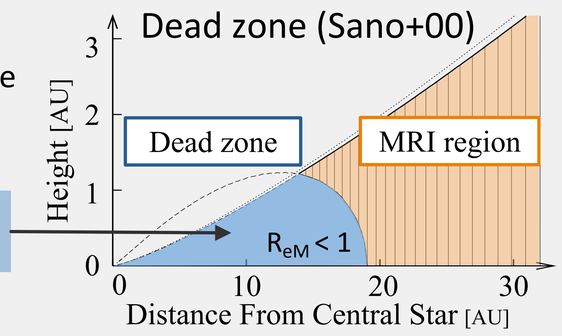


Dusty disk ➡ Balance: Ionization V.S. Dust Capturing
Ionization degree largely depends on amount of dust grains.

Dead Zone

a region where MRI can't drive turbulence because of too low ionization degree.
Magnetic Reynolds# R_{eM} ∝ ionization degree

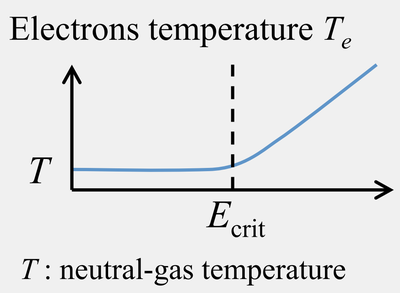
Dust capturing is dominant & cosmic ray can't reach



Electric-field Heating (EH)

Previous assumption : $T_e = T$
Inutsuka & Sano (05) : E ↗ ➡ T_e(E) ↗
: *Electric-field heating of electrons*

Mechanism :
Strong electric fields give enough energy that is transformed to random-motion energy of electrons.

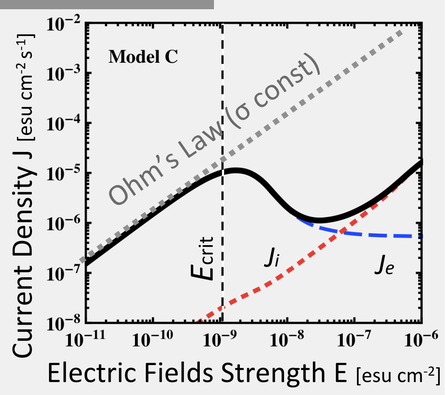


T : neutral-gas temperature

Reduction Ionization Degree by EH of Electrons

(Okuzumi & Inutsuka, submitted: arXiv# 1407.8110)

MHD turbulence
➡ Electric-field heating
➡ Thermal velocity of electrons ⬆
➡ Electrons sticking to grain ⬆
➡ **Ionization degree** ⬇
➡ Electric conductivity ⬇



➡ **MHD turbulence may become weak by this effect.**

PURPOSE

Reduction of ionization degree by EH may weeken MHD turbulence.
BUT, can electric field become strong so that EH occurs ?
We investigate WHERE EH occurs and dust grains capture heated electrons in the dusty disks.

METHOD

Current Density Model in Disk

current density model
- Particles : neutral gas (H2), electrons, positive ions(HCO+), dust aggregates
- Chemical reaction : Ionization, gas-phase recombination, **dust adsorption**
- Recombination rate & adsorption rate are function of T_e .

Calc. current density
Given Electric field *E*
➡ Electric field heating
➡ Number density *e* & +ion n_e n_i from ionization balance
➡ $J = en_e\langle v_e\rangle + en_i\langle v_i\rangle$
$\langle v_e\rangle$, $\langle v_i\rangle$: mean drift velocity of *e*, +ion

Disk model
- MMSN
- ionization source is cosmic ray
- Mid-plane β (:= P_{gas}/P_{mag}) = 100
- Dust grain : radius = 0.1μm, material density = 3g/cm^3
- Dust-gas mass ratio $f_{dg} = 0.01$ (dusty)

➡ Calculate J-E diagrams at each points in the disk, and decide whether reduction ionization degree by EH occurs or not.

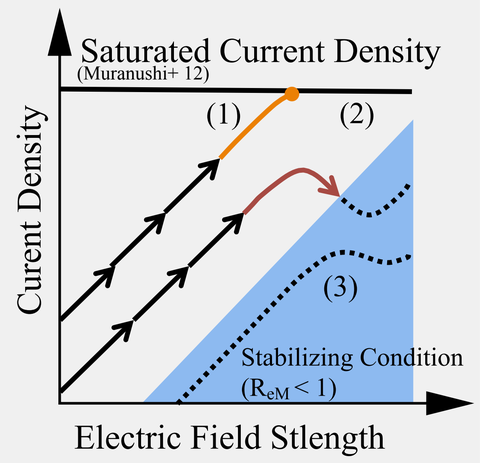
Decision whether EH occurs or not

Assumption in MRI region : Magnetic turbulence amplifies electric field.

(1) Magnetic turbulence is saturated
➡ Keep Saturated Current Density

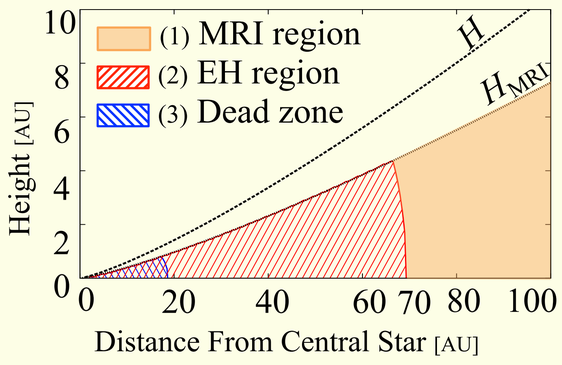
(2) EH of electrons
➡ Electric conductivity reduces
➡ Satisfy stabilizing condition

(3) Satisfy stabilizing condition for all *E*
➡ no MRI



RESULT

(1) – (3) decision mapping in the disk
⬇
Reduction ionization degree by EH occurs in 3-4 times larger region than the dead zone.

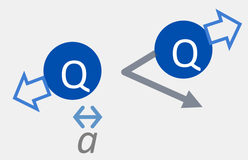


We found EH region is considerably large.

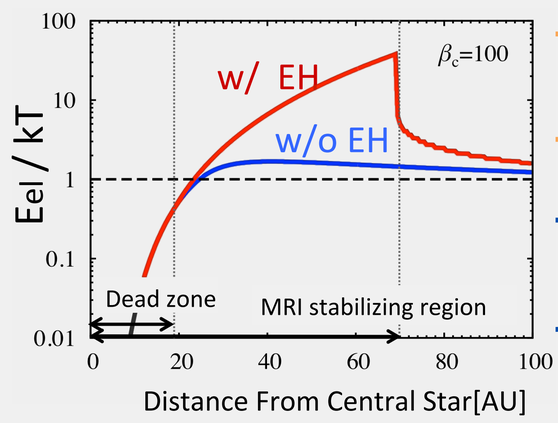
DISCUSSION

More Effective Charge Barrier by EH of Electrons

Charge Barrier (Okuzumi 09)



: Electrostatic repulsion energy *Eel* (~ $Q^2/2a$) > Collisional energy of Brownian motion (~ kT)



Collisional growth is too HARD!

Collisional growth is possible.

NEW problem…

Reference

Okuzumi & Inutsuka, submitted: arXiv# 1407.8110
Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214
Muranushi, T., Okuzumi, S., & Inutsuka, S.-i. 2012, ApJ, 760, 56
Sano, T., Miyama, S. M., Umebayashi, T., & Nakano, T. 2000, ApJ, 543, 486
Inutsuka, S.-i., & Sano, T. 2005, ApJ, 628, L155
Okuzumi, S. 2009, ApJ, 698, 1122

The 7th meeting on Cosmic Dust, 4-8 August 2014, CPS, Osaka, Japan