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# Coevolution of dust grains and protoplanetary disks

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1. Motivation
Protoplanetary disks, which are the birth place of planets are weakly ionized, magnetized plasmas where neutrals, ions, electrons adsorbed onto the dust grains whose size distribution changes on $10^4$–$10^5$ yr time-scales.
Combining global two-fluid non-ideal-MHD simulations that follow grain growth and resistivity evolution with an analytical steady-accretion disk framework, we propose "co-evolution scenario" of dust grains and protoplanetary disks.

2. Numerical discovery: grain-regulated magnetic coupling

When sub-micron grains coagulate to millimetre sizes, the adsorption efficiency onto the grains decrease and the free-electron abundance rises by more than two orders of magnitude. This reduces Ohmic and ambipolar resistivities.
As a result, magnetic braking (the angular momentum removal by the magnetic torque) is moderately strengthened due to the coagulation and changes the disk structures (figure 1).
After sufficient growth of the grains, the disk radial structures settle into characteristic power-law profiles, which is reproduced by modified equations of the conventional steady accretion disk model which consider the magnetic braking, dust growth and ambipolar diffusion.

3. Analytical studies:
Then, we analytically investigate the structure and evolution of protoplanetary disks corresponding to Class 0/I young stellar objects using the modified steady accretion disk model combining an analytical model of envelope accretion.

We found that the disk radius is several AU at disk formation epoch and increases to several 100 AU at the end of the accretion phase. The disk mass is estimated to be $10^{-2}$ $M_{solar}$ for a disk with radius of several 10 AU. These are largely consistent with observed disk size and mass.
We also found that, with typical disk ionization rates and moderate mass accretion rate, magneto-rotational instability (MRI) is suppressed in the disk because of low plasma and efficient ambipolar diffusion.
We argue that the radial profile of specific angular momentum (or rotational velocity) at the disk outer edge should be continuously connected to that of the envelope if the disk evolves by magnetic braking, and should be discontinuous if the disk evolves by internal angular momentum transport process such as gravitational instability or magneto-rotational instability. Future detailed observations of the specific angular momentum profile around the disk outer edge are important for understanding the angular momentum transport mechanism of protoplanetary disks. embedding in a collapsing envelope

4. Conclusions
Grain growth is not a peripheral detail but a primary agent governing the disk evolution. By merging simulation and theory, we provide a coherent evolutionary path that reproduces observed disk sizes and masses, without ad-hoc viscosity prescriptions. We outline concrete diagnostics to discriminate magnetic-braking-dominated evolution versus internal angular-momentum transport driven evolution, which can be used for future high-resolution observations.

References
[1] PASJ, Volume 75, Issue 5, pp.835-852
[2] PASJ, Volume 76, Issue 4, pp.674-687