Effects of dust feedback on evolutions of disks and planets

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Viscous evolution of a gas disk

Protoplanetary disk

Gas drift

Gas

Viscous diffusion

$$V_{vis} \approx -\frac{3\nu}{R}$$

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Gas-dust friction vs. Viscous evolution

\[ \Omega_{\text{gas}} = \Omega_K \sqrt{1 - \eta} \]
\[ \Omega_{\text{dust}} = \Omega_K \]
\[ \eta = -\frac{1}{2} \left( \frac{h}{R} \right)^2 \frac{\partial \ln P}{\partial \ln R} \]

\( \eta > 0 \) in a usual case

Gas

Dust grains

star

Dust drift

Gas drift

Gas-dust friction

Feedback from drifting dust

Viscous diffusion

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Basic equations

Equations of motions of dust grains and disk gas

For the dust grains

\[
\frac{\partial v_R}{\partial t} + (\vec{v} \cdot \nabla) v_R - \frac{v_R^2}{R} = -\frac{GM_\star}{R^2} - \frac{v_R - V_R}{T_{\text{stop}}}.
\]

\[
\frac{\partial v_\phi}{\partial t} + (\vec{v} \cdot \nabla) v_\phi + \frac{v_R v_\phi}{R} = -\frac{v_\phi - V_\phi}{T_{\text{stop}}}.
\]

For the disk gas

\[
\frac{\partial V_R}{\partial t} + (\vec{V} \cdot \nabla) V_R - \frac{V_R^2}{R} = -\frac{c_s^2}{\rho_g} \frac{\partial \rho_g}{\partial R} - \frac{GM_\star}{R^2} + \frac{f_R}{\rho_g}.
\]

\[
\frac{\partial V_\phi}{\partial t} + (\vec{V} \cdot \nabla) V_\phi + \frac{V_R V_\phi}{R} = -\frac{f_\phi}{\rho_g}.
\]

\(f_R, f_\phi\): viscous forces acting unit area in radial and azimuthal directions.

Gas-dust friction

Viscosity

Dust feedback

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Dust and gas velocities in steady state

**• Gas velocity**

\[
V_R(R, z) = \frac{2S't'}{St'^2 + 1} \frac{\rho_d}{\rho_g + \rho_d} \eta V_K + \left( 1 - \frac{1}{St'^2 + 1} \frac{\rho_d}{\rho_g + \rho_d} \right) V_{vis},
\]

\[
V_\phi(R, z) = V_K + \left( \frac{1}{St'^2 + 1} \frac{\rho_d}{\rho_g + \rho_d} - 1 \right) \eta V_K + \frac{St'}{St'^2 + 1} \frac{\rho_g}{\rho_g + \rho_d} V_{vis},
\]

First term: Gas-dust friction, Second term: Gas viscosity

\[
V_{vis} = -\frac{3\nu}{R} \left[ p + \frac{2q}{3} + 2 \left( \frac{z}{h_g} \right)^2 \left( \frac{5q + 9}{6} \right) \right]
\]

\[
\Omega_g = \Omega_K \sqrt{1 - 2\eta},
\]

\[
\eta(R, z) = -\frac{1}{2} \left( \frac{h_g}{R} \right)^2 \left( p + q + \frac{q z^2}{2 h_g^2} \right).
\]

**• Dust velocity**

\[
v_R(R, z) = -\frac{2S't'}{St'^2 + 1} \frac{\rho_g}{\rho_g + \rho_d} \eta V_K + \frac{1}{St'^2 + 1} \frac{\rho_g}{\rho_g + \rho_d} V_{vis},
\]

\[
v_\phi(R, z) = V_K + \frac{1}{St'^2 + 1} \frac{\rho_g}{\rho_g + \rho_d} \eta V_K - \frac{St'}{St'^2 + 1} \frac{\rho_g}{\rho_g + \rho_d} V_{vis},
\]

Dipierro+17, Kanagawa+17
Gas radial velocities in steady state

$V_{vis}$: Viscous drift velocity, $V_K$: Keplerian rotation velocity

$V_R(R,z) = \frac{2St'}{S't^2 + 1 \rho_g + \rho_d} \eta V_K + \left(1 - \frac{1}{S't^2 + 1 \rho_g + \rho_d}\right) V_{vis}$

- Inward drift due to gas viscosity slows down due to dust feedback
- When the gas-dust friction term is larger than the viscous term, the gas can move outward against viscous diffusion.

Dipierro+17, Kanagawa+17
Drift velocities of gas

Solid: Vertical averaged velocity (3D), Dotted: 2D disk (ignore vertical structure)

$\Sigma_d/\Sigma_g=0.01$

Gas moves outward due to dust feedback!

Gas does not feel dust feedback significantly.

$\langle V_R \rangle (R) = \frac{1}{\Sigma_g} \int_{-\infty}^{\infty} V_R \rho_g dz$

Stokes number at the midplane

$St_{mid}$


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When can the dust feedback overcome viscosity?

Above the line, the gas drift velocity is positive (gas move outward)

Solid: Vertical averaged velocity (3D)
Dotted: 2D disk (ignore vertical structure)

$\alpha = 10^{-3}$
$\text{St}_{\text{mid}} \sim 0.1, \Sigma_d/\Sigma_g \sim 0.01$

$\alpha = 10^{-4}$
$\text{St}_{\text{mid}} \sim 0.01, \Sigma_d/\Sigma_g \sim 0.01$


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Hydrodynamic simulations

• 2D (R,φ) simulations by FARGO extended into gas-dust fluid.
  – Ignore the vertical structure of the disk (dust setting, etc)
• Commutating domain (6AU < R < 100AU) divided by radially 512 and azimuthally 128 meshes.
• Initial gas density $\Sigma_g = 540 \text{ g/cm}^2 (R/1\text{AU})^{-1}$.
• Initial dust/gas ratio, $\Sigma_d/\Sigma_g = 0.01$.
• Gas aspect ratio: $h/R = 0.028 (R/1\text{AU})^{1/4}$
• Constant size of dust grains (3cm)
  – Initially $St=0.1$ at 10AU
  – no growth, no fragmentation, no planetesimal formation
• Assuming that the disk size is large enough (dust and gas are supplied from the outside during the simulation)
Effect on viscous disk evolution

\[ \alpha = 10^{-3}, \ \Sigma_d/\Sigma_g = 0.01, \ \text{dust size} = 3\text{cm} \ (\text{initially} \ St = 0.1 \ \text{at} \ 10 \ \text{AU}) \]


Gas radial velocity

\[ V_R (\text{AU/yr}) \]

\[ \times 10^{-5} \]

\[ \begin{align*}
  & t = 3.2 \times 10^4 \ \text{yr} \\
  & t = 9.6 \times 10^4 \ \text{yr} \\
  & t = 1.6 \times 10^5 \ \text{yr}
\end{align*} \]

Gas surface density

\[ \Sigma_g (\text{g/cm}^2) \]

\[ \times 10^{3} \]

\[ \times 10^{2} \]

\[ \times 10^{1} \]

\[ \times 10^{0} \]

\[ \times 10^{-1} \]

\[ \times 10^{-2} \]

\[ \times 10^{-3} \]

\[ R (\text{AU}) \]

\[ R (\text{AU}) \]

Gas moves outward

Gas density decreases because the gas flows outward
But, ... we did not consider

- Size distribution of dust (Dipierro+18)
- 3D simulations (Gonzalez+15,17)
- Dust growth/fragmentation and planetesimal formation (Drążkowska+16, Drążkowska&Alibert 17)

Planetesimals and protoplanets are easy to be formed.

Type I migration is inefficient.
Dust feedback can change a shape of a planet-induced gap

When a large enough protoplanet forms, it would be a giant planet which forms a gap.

Dust size: 3 cm (constant), $\alpha=4 \times 10^{-3}$, $h/R=0.05$, $M_p/M_*=10^{-3}$

Dust grains are highly accumulated at the outer edge $\rightarrow$
Dust feedback must be effective.
Effect of dust feedback on migration of a gap-opening planet

Since the gas density at the outer disk decreases due to the dust feedback, torque exerted from the outer disk decreases.
Effect of dust feedback on migration of a gap-opening planet

2D hydrodynamic simulations (with a migrating planet)
Dust size: 3 cm (constant), $\alpha=3 \times 10^{-4}$, $h/R=0.05$, $M_p/M_*=10^{-3}$

Because of weaker negative torque from the outer disk, the planet can migrate outward.

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Outward migration

Gas surface density

$\Sigma_{\text{gas}}/\Sigma_{\text{gas, ini}}(R_p)$

$R/R_p$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$ $1.2$ $1.4$ $1.6$ $1.8$ $2.0$ $2.2$ $2.4$

Gas decreases

$\Sigma_{\text{gas}}/\Sigma_{\text{gas, ini}}(R_p)$

$R_p$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$ $1.2$ $1.4$ $1.6$ $1.8$ $2.0$ $2.2$ $2.4$

Outward migration

$0.0$ $0.5$ $1.0$ $1.5$ $2.0$ $\times 10^4$

Because of weaker negative torque from the outer disk, the planet can migrate outward.

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Summary

• Dust feedback can help to make planets and save them from fast inward migration.

• The gas surface density within 10 AU can decrease due to the dust feedback.
  – Since the dust-to-gas mass ratio decreases, planetesimals and protoplanets could easy to be formed.
  – Since Type I migration is inefficient, the planets which are formed in this region can avoid too fast inward migration.

• Dust feedback reduce the torque exerted from the outer disk
  – The gap-opening planet can migrate outward when the planet is massive (Jupiter size) and viscosity is relatively low.
  – The gap-opening planet can survive for a long time.