Location and shape of the water iceline in protoplanetary disks

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A primer on protoplanetary disks

Young planets in accretion disks interact gravitationally with their environment. Angular momentum exchange between planet–disk leads to the formation of spiral arms. These spirals can steepen into shocks, delivering large amounts of heat to the disk. The planet can also carve a low-density gap around its orbit. This leads to a local drop in temperature. Both of these effects influence the overall disk thermal structure, introducing non-axisymmetric features and partitioning the disk into regions with different radiative properties.

Motivation: planet shock heating

Viscosity and stellar irradiation typically act as primary heating agents in protostellar disks. However, Rafikov (2016) showed that shock heating by spiral waves launched by planets can be a substantial if not dominant heat source in the inner disk.

We study how the water iceline ($T(r_{ice})$ = 170 K) is affected by this shock heating.

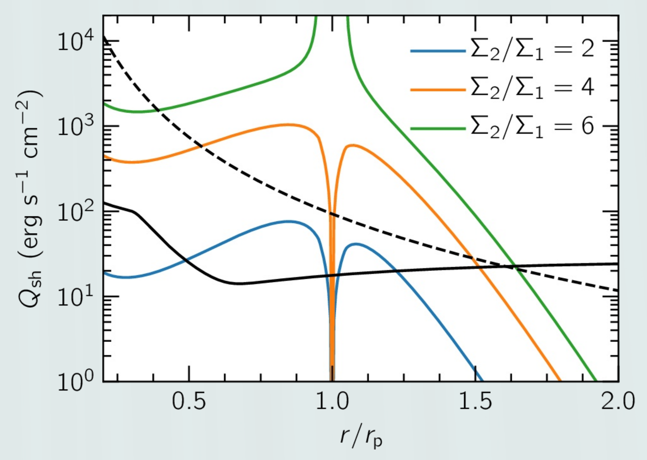


Figure 1: An estimate of the spiral shock heating rate for different shock strengths (post- to pre-shock density), compared to the irradiative (solid, black line) and viscous (black, dashed) heating rates for a sample model.

Physics and numerics

We perform 2D hydrodynamics simulations with radiation transport using the PLUTO package (Mignone et al., 2007). The energy equation and its source terms read:

$$\frac{\mathrm{d}\Sigma e}{\mathrm{d}t} = \gamma \Sigma e \nabla\cdot\mathbf{v} + Q_{\mathrm{visc}} + Q_{\mathrm{irr}} - Q_{\mathrm{cool}}$$

$$Q_{\mathrm{visc}} = \frac{1}{2\nu\Sigma}\left(\sigma_{rr}^2 + 2\sigma_{r\phi}^2 + \sigma_{\phi\phi}^2\right) + \frac{2\nu\Sigma}{9}(\nabla\cdot\mathbf{v})^2$$

$$Q_{\mathrm{irr}} = 2\frac{L_*}{4\pi r^2}(1-\epsilon)\left(\frac{\mathrm{d}\log H}{\mathrm{d}\log r} - 1\right) h\frac{1}{\tau_{\mathrm{eff}}}$$

$$Q_{\mathrm{cool}} = 2\sigma_{\mathrm{SB}}\frac{T}{\tau_{\mathrm{eff}}}$$

where $\nu = \alpha c_s H$, $\tau = \frac{1}{2}\frac{1}{\sqrt{2\pi}}\kappa\Sigma$, $\tau_{\mathrm{eff}} = \frac{3\tau}{8} + \frac{\sqrt{3}}{4} + \frac{1}{4\tau}$,

and $M_* = \mathrm{M}_\odot$, $L_* = \mathrm{L}_\odot$, $\epsilon = 0.5$, $\frac{\mathrm{d}\log H}{\mathrm{d}\log r} = \frac{9}{7}$.

The planet's gravitational force is given by:

$$\mathbf{g} = \mathbf{g}_{\mathrm{p}} + \mathbf{g}_{\mathrm{in}} = -\frac{GM_{\mathrm{p}}}{(r_{\mathrm{e}}^2+\epsilon^2)^{3/2}}\mathbf{r}_{\mathrm{e}} - \frac{GM_{\mathrm{p}}}{r_{\mathrm{p}}^3}\mathbf{r}_{\mathrm{p}}, \quad \mathbf{r}_{\mathrm{e}} = \mathbf{r} - \mathbf{r}_{\mathrm{p}}.$$

Initial and boundary conditions

For various disk accretion rates $\dot{M}$ [M$_\odot$/yr] and viscosities α, we evolve disks to viscous and thermal equilibrium and keep those that are gravitationally stable.

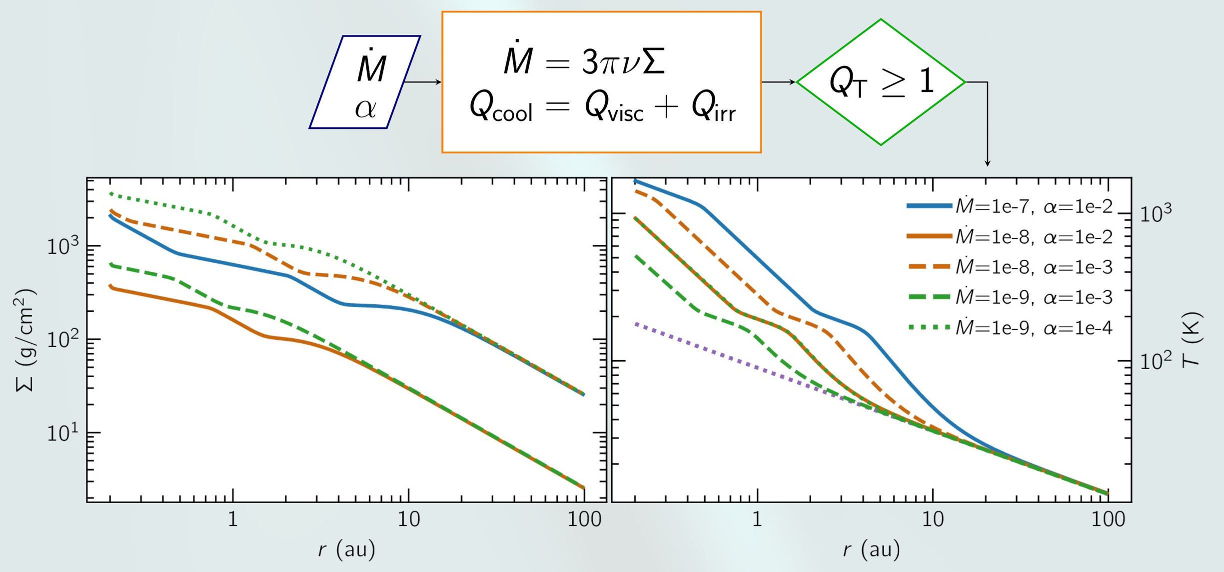


Figure 2: Initial profiles. A purple line marks our effective temperature floor.

In each model, a planet with mass M_p is embedded at a distance r_p from the star and kept on a circular orbit until equilibrium is reached. We utilize wave-damping boundaries.

Results: iceline displacement and/or deformation

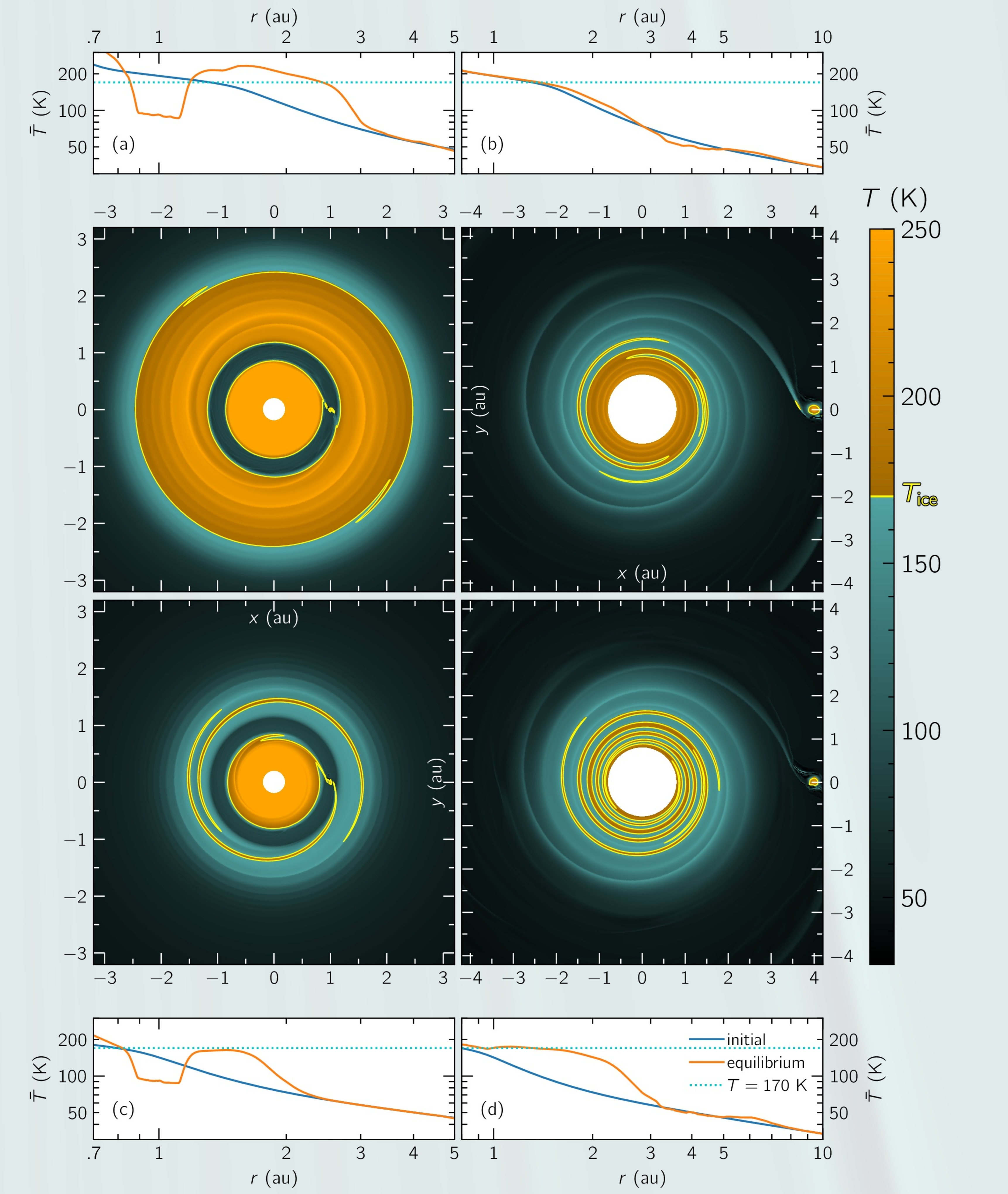


Figure 3: Azimuthal structure of the iceline for 4 models. The two colormaps denote the blue, "cold" ($T<T_{ice}$) and orange, "hot" ($T>T_{ice}$) disk, respectively, with a yellow line separating the 2 regions ($T=T_{ice}$).

a) M_p=100 M_E, $\dot{M}=10^{-9}$, $\alpha=10^{-4}$, r_p=1 au: A gap opens and a hot ring forms in the outer disk.

b) M_p=1 M_J, $\dot{M}=10^{-8}$, $\alpha=10^{-2}$, r_p=4 au: The iceline shows azimuthal features but is not significantly displaced.

c) M_p=100 M_E, $\dot{M}=10^{-9}$, $\alpha=10^{-3}$, r_p=1 au: The gap separates the hot and cold disk. Shock heating increases temperatures in the outer disk high enough to allow the outer spirals to cross the iceline threshold. This could lead to the formation of "slush islands", a mixture of ice and water vapor along the spirals.

d) M_p=1 M_J, $\dot{M}=10^{-9}$, $\alpha=10^{-3}$, r_p=4 au: The iceline contours capture the trajectories of spirals in the inner disk, far away from the planet.

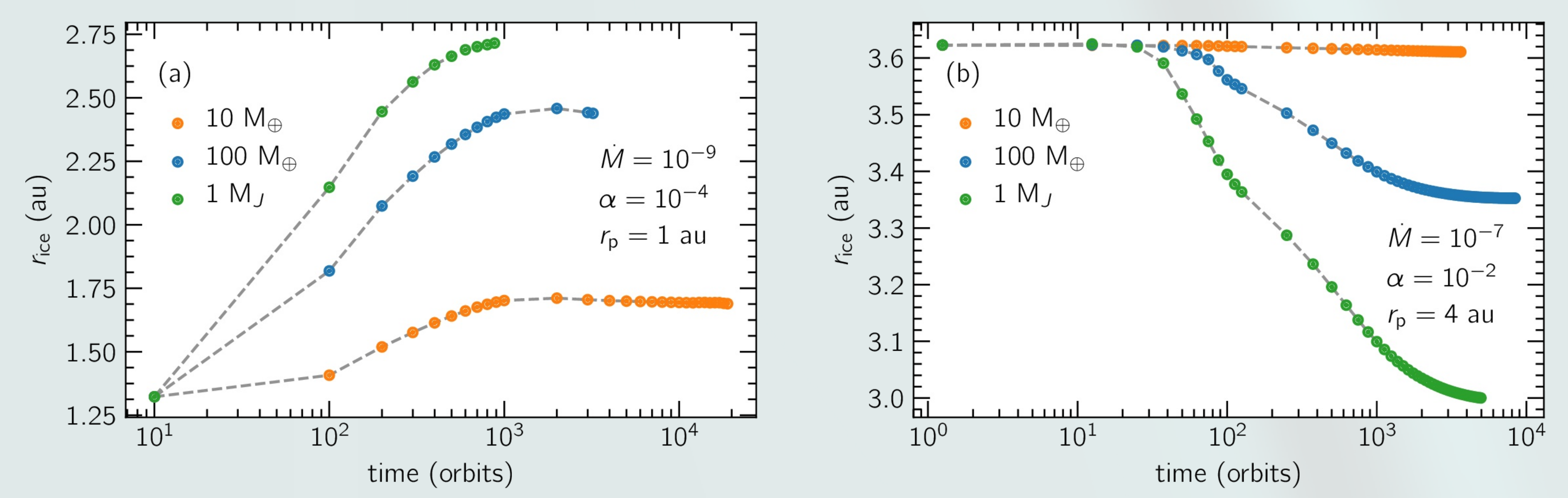


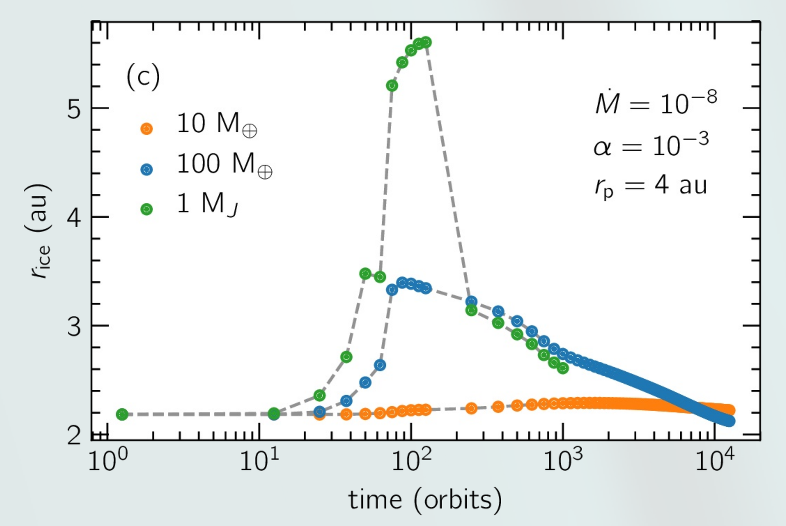
Figure 4: Azimuthally-averaged iceline location for 3 sets of models. Depending on its initial location relative to the planet, the iceline is exposed to both shock heating and gap cooling.

a) Shock heating pushes the iceline outwards.

b) The iceline recedes to the inner gap edge.

c) Shock heating and gap cooling balance out.

Legend: planet mass. Annotated: model parameters.



Conclusions

- Shock heating is strongest in disks with small aspect ratios, whereas irradiative heating overpowers shocks at large radii.
- Low viscosity further supports shock heating.
- Massive disks trap heat more efficiently, enhancing shock heating.

→ Shock heating by a planet can be a significant heating agent in the optically thick inner disk.

- In an optically thick disk, a gap can reshape the iceline into a hot ring.
- In cooler disks, the iceline can take the form of "slush islands".

→ The iceline can be moved/deformed due to shock heating, with possible implications on planetesimal growth in the midplane.

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