Planet-induced gaps and rings in ALMA disks: the role of in-plane radiation transport

A. Ziampras[1], R. P. Nelson[1], R. R. Rafikov[2]

1) Astronomy Unit, Queen Mary University of London, UK; 2) DAMTP, University of Cambridge, UK

Motivation: planet-driven gap opening

ALMA observations in continuum emission reveal rich annular structure in protoplanetary disks [1]. **Planet–disk interaction** is a popular explanation, supported by hydrodynamical models [2].

Recent work has shown that **radiative cooling influences the angular momentum transported by spiral arms**, deciding the number, position, and depth of **rings and gaps** that a planet can impose on the disk [3][4].

However, radiation transport has only been treated as a local cooling law, not taking into account the diffusion of heat along the disk plane [5]. With state-of-the-art 2D hydrodynamical models, we aim to quantify the **effect of in-plane diffusion on planet-induced gap opening**.

Angular momentum flux (AMF)

To measure gap opening, a useful quantity is the **angular momentum flux** (AMF) of spiral arms

$$F_J(R) = R^2\bar{\Sigma}(R)\oint \delta u_R \delta u_\phi \, \mathrm{d}\phi, \qquad \delta u_x = u - \bar{u}_x$$

We then compute a metric for the **total angular momentum**, normalized to that for an adiabatic spiral

$$G = \frac{\int F_J \, \mathrm{d}R}{\int F_J^{\mathrm{ad}} \, \mathrm{d}R}$$

A higher (lower) G translates to more (fewer) gaps.

Disk model and thermodynamics

Disk temperature is set by a balance between several mechanisms:

- stellar irradiation

$$Q_{\mathrm{irr}} = 2\frac{L_\star}{4\pi R^2}\frac{\theta}{\tau_{\mathrm{eff}}}, \qquad \theta \approx R\frac{\mathrm{d}H}{\mathrm{d}R}$$

- surface cooling

$$Q_{\mathrm{surf}} = 2\sigma_{\mathrm{SB}}\frac{T^4}{\tau_{\mathrm{eff}}}, \qquad \tau_{\mathrm{eff}} = \frac{3\kappa_{\mathrm{R}}\Sigma}{16} + \frac{\sqrt{3}}{4} + \frac{1}{2\kappa_{\mathrm{R}}\Sigma}$$

- in-plane radiative diffusion (FLD)

$$Q_{\mathrm{rad}} = 2H\nabla\cdot\left(\lambda\frac{4\sigma_{\mathrm{SB}}}{\kappa_{\mathrm{R}}\rho_{\mathrm{mid}}}\nabla T^4\right)$$

- small perturbations due to shock heating by the planet's spirals.

The energy equation is then:

$$\frac{\mathrm{d}}{\mathrm{d}t}(\Sigma c_{\mathrm{v}} T) = -P\nabla\cdot\vec{u} + Q_{\mathrm{irr}} - Q_{\mathrm{surf}} + Q_{\mathrm{rad}}$$

We compare the following models:
adiabatic: shock heating only;
isothermal: prescribed, fixed $T(R)$;
surface cooling: no in-plane diffusion;
fully radiative: all terms included.

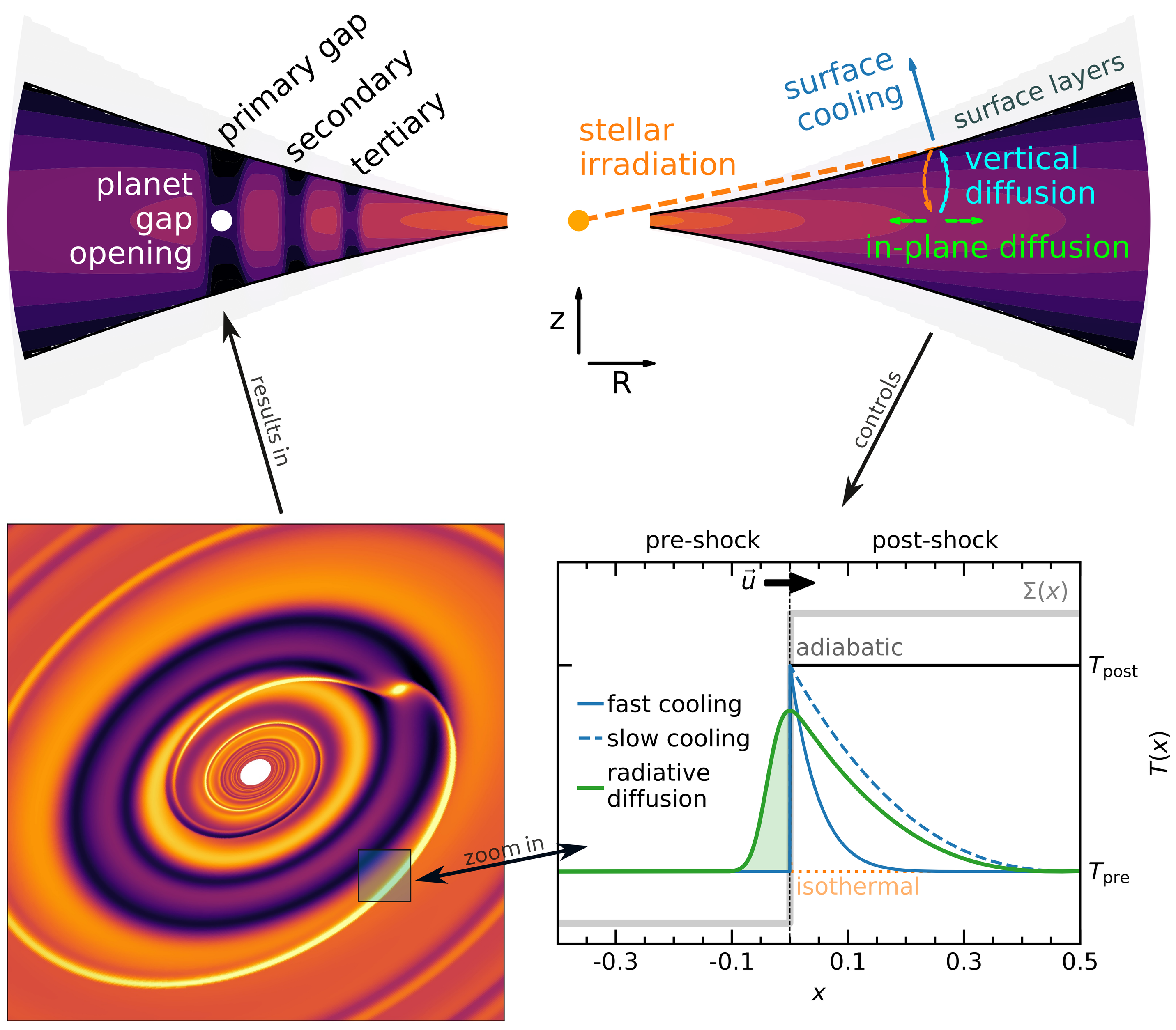

Figure 1: Top: edge-on illustration of a protoplanetary disk with an embedded planet. The temperature structure is set by various radiative processes (right half), which affect gap opening (left half). A single planet can open multiple gaps under certain conditions.
Bottom left: view of a disk with an embedded planet and its signature spiral arms. These spirals eventually shock, depositing angular momentum locally and gradually opening one or more gaps. Bottom right: a "zoom in" on a 1D spiral shock front. Cooling determines its temperature structure, affecting the gap opening process.

Dependence of gap opening on the cooling timescale

We run hydro models (PLUTO) with constant κ_{R}, Σ, β_{surf}, where

$$\beta_{\mathrm{surf}} = \frac{\Sigma c_{\mathrm{v}} T}{Q_{\mathrm{surf}}}\Omega_{\mathrm{K}}$$

is the surface cooling timescale.

We find that **in-plane diffusion enhances** (damps) **gap opening** in the fast- (slow-) cooling regimes!

This happens because in-plane diffusion acts as an additional cooling channel, **reducing the effective cooling timescale**.

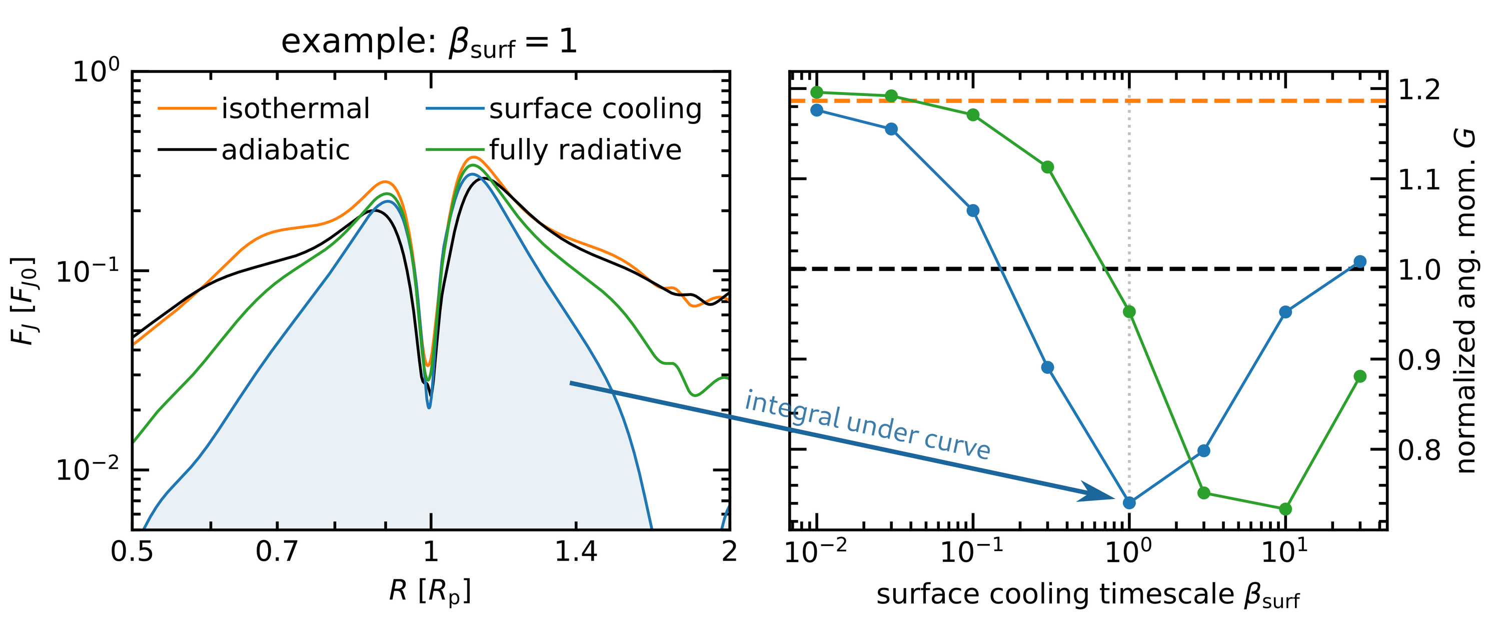

Figure 2: Left: AMF for different cooling prescriptions. Including in-plane diffusion increases the AMF, enhancing gap opening. Right: the parameter G as a function of the surface cooling timescale. Two cooling regimes appear, showing that in-plane diffusion (included in green curves) enhances/damps gap opening when cooling is fast/slow.

Conclusions

- Radiation transport is crucial to planet-induced gap opening via damping of spiral shocks.
- In-plane radiative diffusion provides an additional cooling channel, resulting in effectively faster cooling.
- Including in-plane radiation transport results in a **higher spiral AMF** and therefore **more, shallower gaps** in the **fast-cooling** regime ($\beta_{\mathrm{surf}} < 1$), and **vice versa** for $\beta_{\mathrm{surf}} > 1$.

Our cooling model is especially relevant for ALMA disks, where often $\beta_{\mathrm{surf}} \sim 0.1$–$10$. It can then help constrain the parameter space when modeling substructures with planet–disk interaction.

Cooling in ALMA disks

Modeling rings and gaps as the result of planet–disk interaction is very sensitive to cooling [2][3].

In particular, many observed rings/gaps fall in the regime where **in-plane cooling is especially important** ($\beta_{\mathrm{surf}} \sim 1$)!

A more accurate cooling model can **constrain the parameter space.**

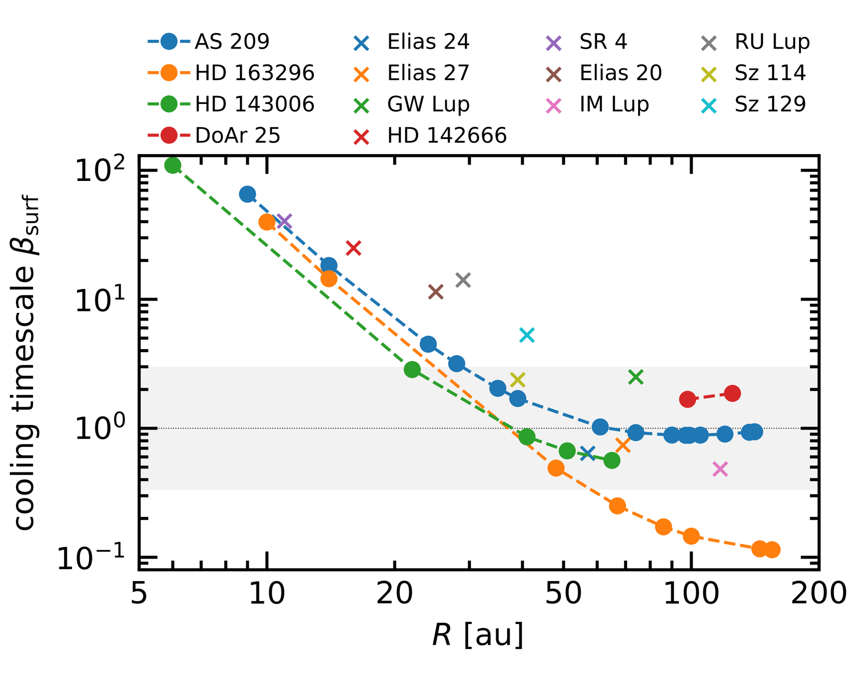

Figure 3: Ballpark estimates of the cooling timescale in various DSHARP systems with substructure (very sensitive on model!).

Application to ALMA disks

To showcase our findings we model AS 209 and Elias 20, two systems that represent the fast- and slow-cooling regimes with our approach (see Fig. 3).

Here, we use realistic disk parameters, an opacity model, and dust post-processing to produce synthetic images.

We compare surface-cooled only to fully radiative models, and confirm that **models with in-plane diffusion fit observations best**, enhancing/suppressing substructure in AS 209/Elias 20.

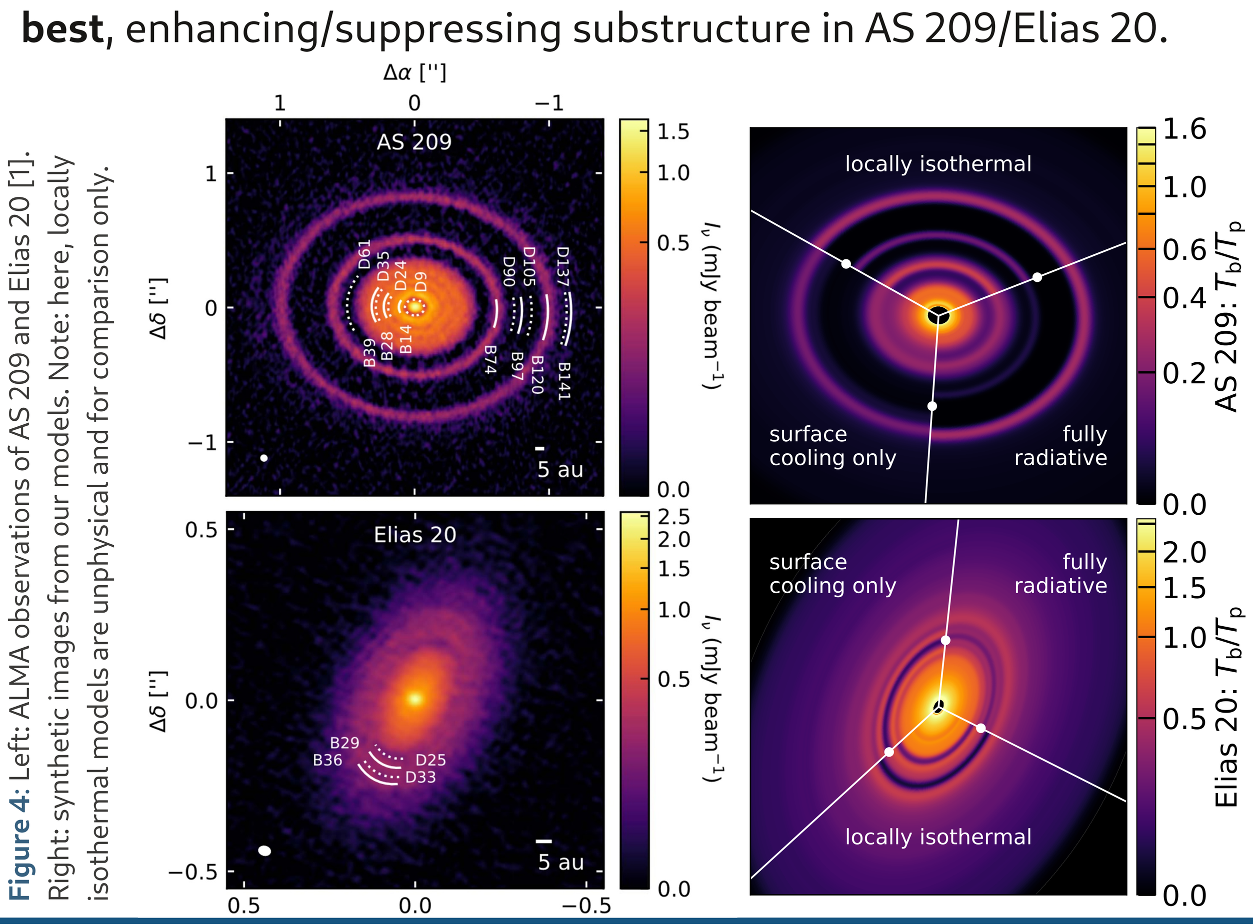

Figure 4: Left: ALMA observations of AS 209 and Elias 20 [1]. Right: synthetic images from our models. Note: here, locally isothermal models are unphysical and for comparison only.

Are you interested in mimicking the effects of surface cooling and in-plane diffusion on the AMF by planet-driven waves in your hydro models? Here is an approximate recipe with similar results:

$$\frac{\mathrm{d}}{\mathrm{d}t}(\Sigma c_{\mathrm{v}} T) = Q_{\mathrm{relax}} = -4\Sigma c_{\mathrm{v}}\frac{T - T_0}{\beta_{\mathrm{tot}}}\Omega_{\mathrm{K}}, \qquad \beta_{\mathrm{tot}}^{-1} = \beta_{\mathrm{surf}}^{-1} + \beta_{\mathrm{mid}}^{-1}$$

With $\beta_{\mathrm{mid}} = \frac{\Omega_{\mathrm{K}}}{\eta}\left(H^2 + \frac{1}{3\kappa_{\mathrm{R}}^2\rho_{\mathrm{mid}}^2}\right)$, $\eta = \frac{16\sigma_{\mathrm{SB}}T^3}{3\kappa_{\mathrm{R}}\rho_{\mathrm{mid}}^2 c_{\mathrm{v}}}$, and your T_0.

Bonus

References

[1] Huang et al. (2018), ApJ, **869**, L42
[2] Zhang et al. (2018), ApJ, **869**, L47
[3] Ziampras et al. (2020), A&A, **637**, A50
[4] Miranda & Rafikov (2019), ApJ, **878**, L9
[5] Miranda & Rafikov (2020), ApJ, **904**, 121

About me

Alex Ziampras (he/him)
Postdoc at QMUL
E-mail: a.ziampras@qmul.ac.uk

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