Stellar irradiated discs

and implications on migration of embedded planets

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Hydrodynamical Simulations

Low-mass planets in discs around stars:

- isothermal discs: inward migration
- fully radiative discs:
  Equilibrium structure of disc determined by viscous heating and cooling. Planets can migrate outwards (e.g. Paardekooper, S.-J. & Mellema, G. 2006, Kley et al. 2009).
- At zero-torque radius (e.g. Bitsch & Kley, 2011) the merging of protoplanets might be easier.
- Stellar irradiated discs:
  Observations: flared discs, contrary to fully radiative case. The energy of the star heats the upper layers of the disc and influences the disc structure. Flaring with $H/r \propto r^{2/7}$ (e.g. Chiang & Goldreich, 1997).

$\Rightarrow$ Influence on migration of embedded objects in the disc?

Energy equation for stellar irradiated disc

Coupled energy equation:

$$\frac{\partial E_R}{\partial t} + \nabla \cdot \mathbf{F} = \rho \kappa_P(T,P)[B(T) - cE_R]$$

$$\left[\frac{\partial \epsilon}{\partial t} + (\mathbf{u} \cdot \nabla)\epsilon\right] = -P\nabla \cdot \mathbf{u} - \rho \kappa_P(T,P)[B(T) - cE_R] + S + \Phi$$

- E_R radiation energy density
- $\epsilon = c_v \rho T$ thermal energy density
- Φ viscous heating, $\nabla \mathbf{F}$ radiative diffusion:

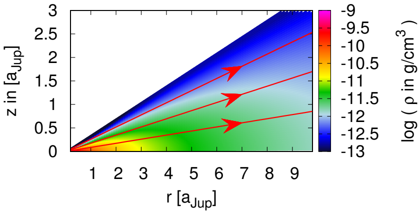
$$\nabla \mathbf{F} = -\frac{\lambda c}{\rho \kappa_R} \nabla E_R$$

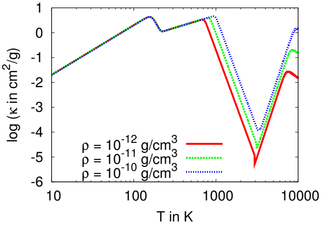
- Stellar heating from the star (V Volume of grid cell, τ optical depth):

$$S = \frac{R_\star^2}{V} \sigma T_\star^4 \mathrm{e}^{-\tau} (1 - \mathrm{e}^{-\rho_i \kappa_{OP,i} \Delta r})$$

Numerical setup

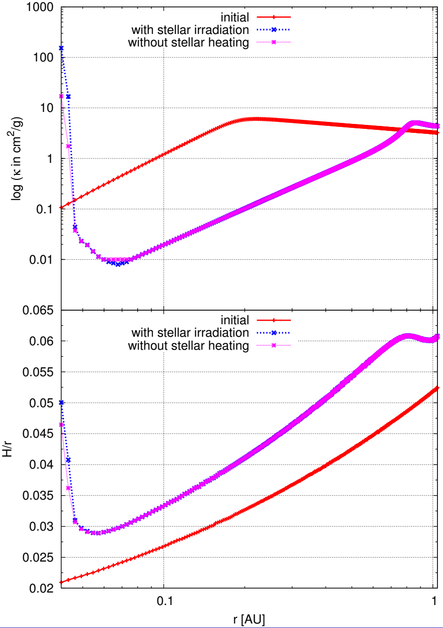
- 3D spherical hydrodynamics in r,θ, ϕ, but only r-θ plane with 384 $\times$ 32 active cells used (axisymetric)
- Star as a point source: stellar irradiation propagates on rays along constant θ-lines
- Parameters of the initial setup:
  - constant viscosity $\nu = 10^{15}\text{cm}^2/\text{s}$
  - $M_\star = 1M_\odot$ Star, $R_\star = 3.0R_\odot$, $T_\star = 5600$K
  - initially flared disc profile with $H/r \propto r^{2/7}$
- varying opacity by Bell & Lin, 1994





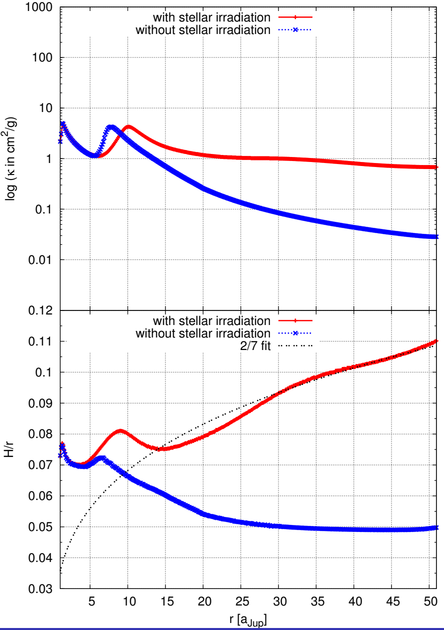
Inner disc with and without stellar heating

- Inner disc structure dominated by viscosity
- Transitions in opacity profile translate to changes in H/r
- Inner rim due to increase in opacity, but: opacity drops for even higher temperatures
- Inner disc shields outer disc from stellar irradiation



Fully radiative vs. stellar heated disc

- Inner parts dominated by viscosity: similar structure
- Outer parts dominated by stellar heating: flared disc
- Flared disc with $H/r \propto r^{2/7}$ as in Chiang & Goldreich, 1997
- Bumps in disc shield outer disc from stellar irradiation



Migration of the disc via Torque formula

- Torque formula by Paardekooper et al. (2011):

$$\Gamma_{tot} = \Gamma_L + \Gamma_c$$

  with Γ_L Lindblad torque, Γ_c corotation torque.

- Lindblad torque:

$$\gamma \Gamma_L / \Gamma_0 = -2.5 - 1.7\beta + 0.1\alpha \ , \quad \Gamma_0 = \left(\frac{q}{h}\right)^2 \Sigma_P r_p^4 \Omega_P^2 \ ,$$

  where α denotes the negative slope of the surface density profile $\Sigma \propto r^{-\alpha}$, β refers to the slope of the temperature profile $T \propto r^{-\beta}$, and γ is the adiabatic index of the gas.

- Corotation part much more complicated!

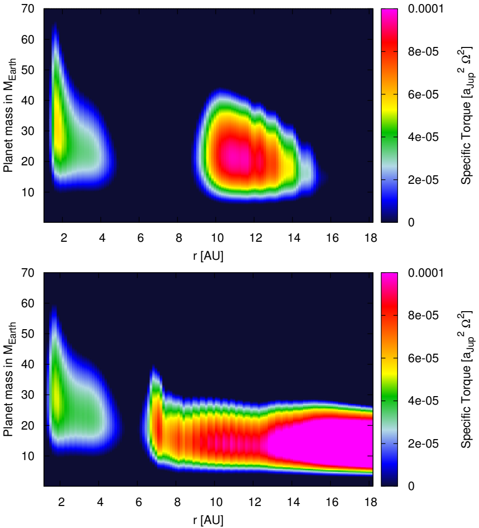
  $\Rightarrow$ Gradients in disc determine migration!

Torque acting on planets

top: stellar irradiated disc

black colour in plot: inward migration

bottom: fully radiative disc



Summary and Conclusions

- Viscosity dominates the disc structure in the inner disc
- Stellar irradiation determines the disc structure in the outer parts
- Outer disc: $H/r \propto r^{2/7}$
- Shadowing effect due to opacity bumps
- Shadowing of disc: explanation for transition discs?
- Migration:
  - 2 different located zero-torque radii
  - Reduced region of outward migration for stellar irradiated discs
  - Smaller region where cores can merge: better chance of growing?

Reference: Stellar irradiated discs and implications on migration of embedded planets I: equilibrium discs, submitted to A&A