Gravitational Instability in Irradiated Protoplanetary Discs

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Background

Gravitational instability (GI) is important in disc evolution for driving angular momentum transport and as a potential formation mechanism of binary stars and giant planets.

It is commonly expected in young, massive discs due to the requirement for a low Toomre parameter: $Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1-2$

Previous studies have emphasised the significance of cooling time, which limits regions of the disc where GI is important to outer radii. The saturation of GI to a quasi-steady state is sensitive to thermal effects and in the outer disc, heating is expected to be dominated by stellar irradiation.

The regime of short cooling times and strong irradiation is important to understand but the behaviour of these discs and the impact on GI is currently unclear.

In this work, we focus on how irradiation is incorporated in 2D hydrodynamic simulations and it's effect on disc stability.

Simulations

We use local 2D hydrodynamic simulations to directly compare a constant heating rate per unit mass and per unit area using the same code (*Athena*)

Inputs

$Q_{\rm irr} = \frac{c_{s,\rm irr}\Omega_0}{\pi G \Sigma_0}$ Effective Q the system would obtain due to external irradiation in the absence of GI

$\beta = \tau_c \Omega_0$ Cooling parameter as the ratio of the cooling and dynamical timescales

Outputs

$Q_{\rm sat} = \langle Q \rangle$ Average Q of the saturated gravitoturbulent state

$\alpha = \frac{\nu_t}{c_s H}$ Effective viscosity parameter

Internal Energy Density Equation:

$$\partial_t U + (\boldsymbol{u}\cdot\nabla)U + \gamma U(\nabla\cdot\boldsymbol{u}) = -\frac{U}{\tau_c} + \begin{cases} \frac{U_{\rm irr}}{\tau_c} \\ \frac{\Sigma}{\Sigma_0}\frac{U_{\rm irr}}{\tau_c} \end{cases}$$

Radiative cooling — Heating by irradiation

Assuming thermal equilibrium:

$$\alpha = \frac{4}{9\gamma(\gamma-1)\beta}\left(1 - \frac{Q_{\rm irr}^2}{Q_{\rm sat}^2}\right)$$

Predictions from linear stability analysis:

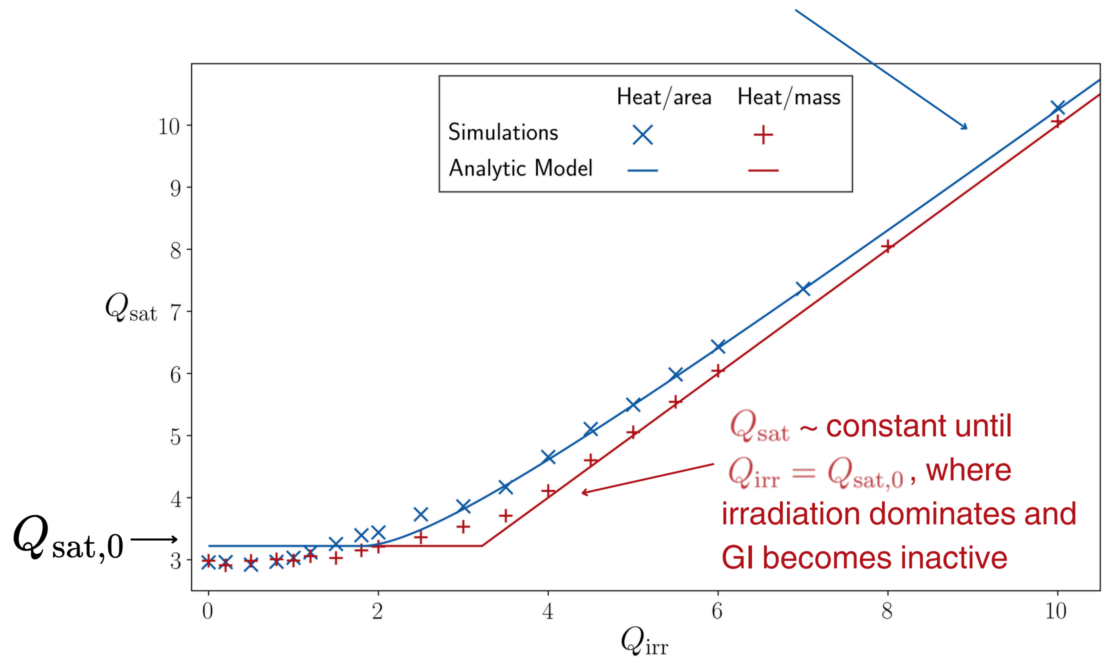
Heating per unit area => unstable modes at arbitrarily large amounts of irradiation

Heating per unit mass => GI solutions only for low levels of irradiation

Our analytic model requires Qsat and a values which satisfy both the linear theory and equation for thermal equilibrium. There are no valid solutions below $Q_{\rm sat} = 3.2$, which we take to be $Q_{\rm sat,0}$, the value of $Q_{\rm sat}$ in the absence of irradiation.

Results

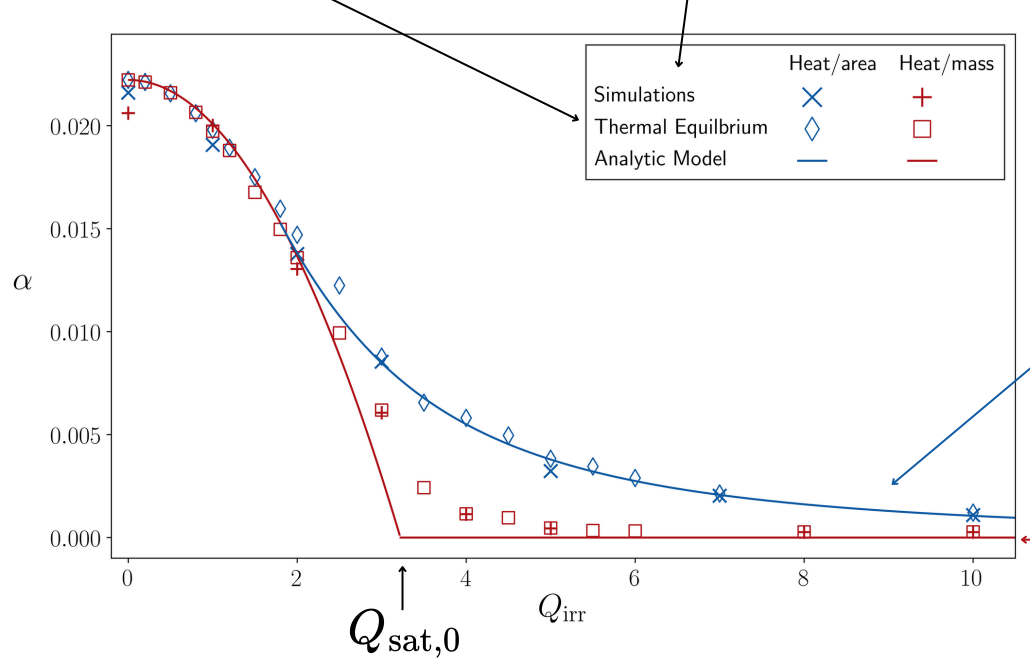
$Q_{\rm sat}$ increases with $Q_{\rm irr}$ such that it is always greater than the minimum level imposed by irradiation
Discs are expected to be unstable only when the Toomre Q parameter is close to the classical criterion for instability (Q<1).
These simulations show GI is active even at larger values of Q



Using the thermal equilibrium equation with $Q_{\rm sat}$ measured from simulations

Direct measurements combining gravitational and Reynolds stresses:

$$\alpha = \frac{2}{3\langle\Sigma c_s^2\rangle}(\langle G_{xy}\rangle + \langle H_{xy}\rangle)$$



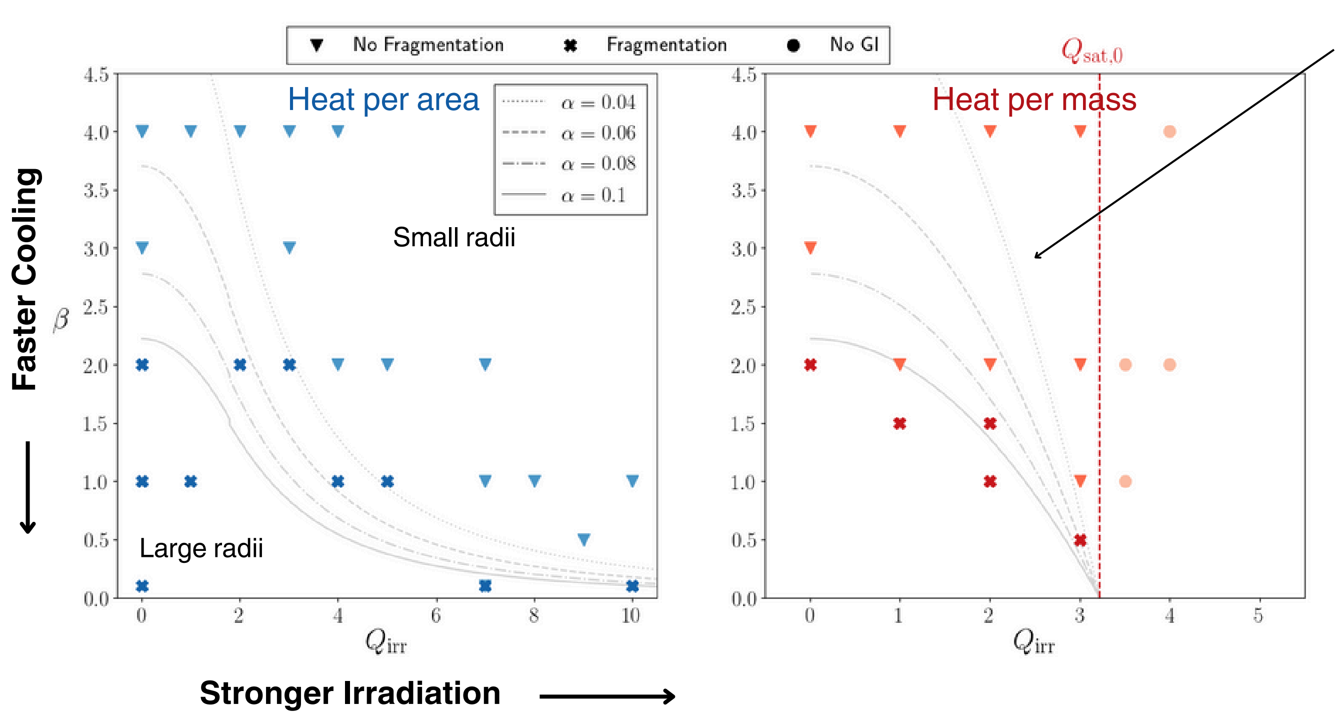
Supplying heat at a constant rate per unit mass will preferentially heat overdensities, enhancing the stabilising effect of pressure gradients. This is not the case when heating per unit area, so cooling is still effective. Imposing a greater amount of irradiation will raise the minimum temperature of the system, but overdensities are still able to form and disrupt in the familiar quasi-steady state of GI.

As irradiation increases, the effective viscosity due to GI decreases, but remains finite

α goes to zero, matching the current expectation that irradiated discs will be stable against GI

Fragmentation

For a disc to fragment and form bound objects that could evolve to planets, brown dwarfs or binary companions, GI must be active and the cooling time must be short. If the cooling time is too long, overdensities won't be able to collapse before they are heated due to shocks.



Lines of constant α indicate a maximum viscous stress the disc can withstand, above which fragmentation occurs

When heating per area, highly irradiated discs can fragment for short enough cooling timescales. This suggests fragmentation would occur at larger radii since β is a steeply decreasing function of radius.

Summary

- The effect of stellar irradiation on local 2D hydrodynamic simulations of self-gravitating discs depends on whether irradiation is incorporated as a constant heating rate per unit mass or per unit area
- When heating per mass, the instability is only active for low levels of irradiaition
- When heating per mass, GI persists for large levels of irradiation with high values of the Toomre Q parameter and fragmentation can occur in the highly irradiated regime for short enough cooling timescales
- Heating per unit area may be more physically valid since discs are expected to be optically thick to incident irradiation at large radii
- Work is ongoing to test whether this effect remains with more realistic cooling and in 3D simulations

References
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