Characterizing Gravitational Instability in Protoplanetary Disks around Hosts with Different Stellar Masses

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Introduction

- Protoplanetary disks are the birthplace of planets. In sufficiently massive disks, self-gravity can become dynamically important.
- The stability of such disks is commonly characterized by the Toomre Q parameter[1]:

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

For $Q \lesssim 1$, disk becomes gravitationally unstable and two things can happen:
- If cooling is inefficient, the disk settles into a quasi-steady state.
- If cooling is efficient, the instability grows and the disk fragments.

- These fragments can go on to form wide-orbit gas giants and brown dwarfs[2]
- Stellar irradiation has been shown to suppress gravitational instability (GI) because of the dominating thermal effects of the star[3]
- This work investigates how the strength of GI and the likelihood of fragmentation depends on the mass of the disk host star.

Methods

- Simulations are carried out using 3D smoothed particle hydrodynamics code, PHANTOM.[4]
- Thermodynamics are modeled using radiative transfer by assigning each particles a mean optical depth $\bar{\tau}$ to capture both optically thick and thin regions.[5]
- External heat comes from stellar irradiation modeled via

$$T = \frac{L_*}{4\pi\sigma R^2}$$

Simulation parameters

- Stellar Masses: 0.5, 0.75, 1, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75 $M_\odot$
- SPH particles: 2,000,000
- $\alpha_{SPH}, \beta_{SPH}$: 0.1, 0.2 and 1,2
- Disk-to-star mass ratio: 0.25
- Outer Radius[6]: $R_{out} = 2\left(\frac{M_{disc}}{5\times10^{-4} M_\odot}\right)^{\frac{5}{8}}$
- Inner radius: $R_{in} = 0.1 R_{out}$

Results

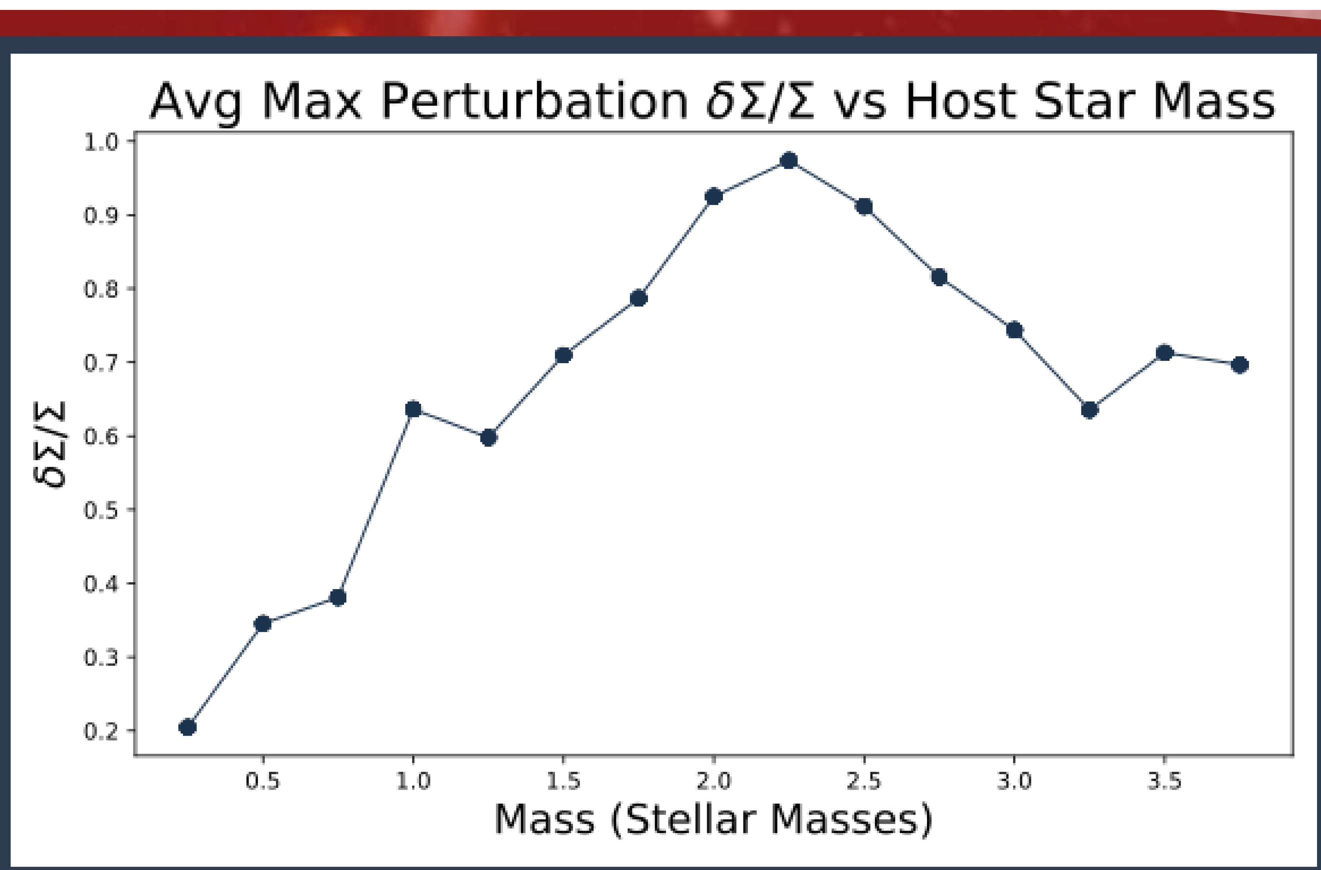

Figure 1. The average maximum surface density perturbation amplitude as a function of disk host stellar mass with $\alpha_{SPH} = 0.1$. There is an increase in amplitude as you increase mass to 2 $M_\odot$ and decrease following that.

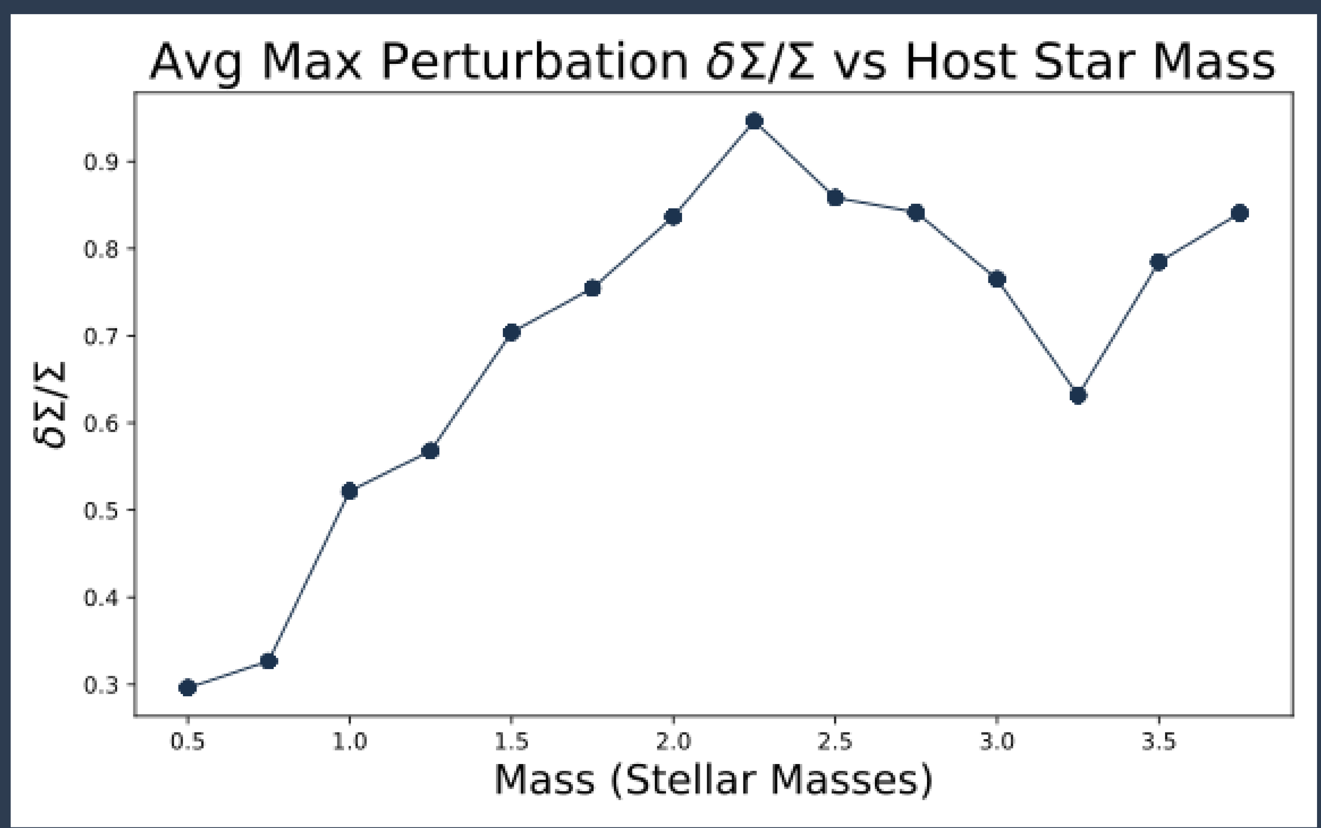

Figure 2. The average maximum surface density perturbation amplitude as a function of disk host stellar mass with $\alpha_{SPH} = 1$. There is a similar trend to figure 1 but with a noticeable dip likely due to artificial viscous effects.

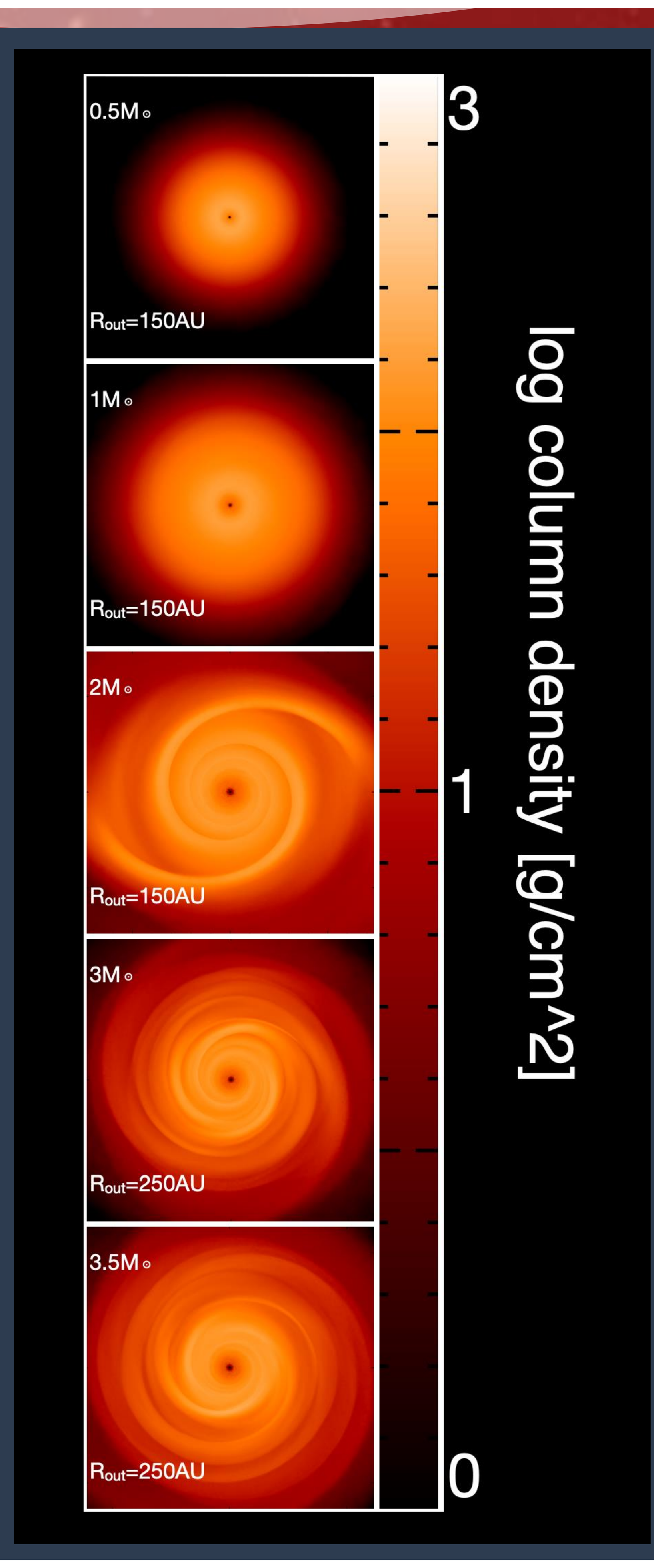

Figure 3.) 3D SPH results for the 0.5, 1, 2, 3, and 3.5 $M_\odot$ star systems at their final state. The 0.5 and 1 $M_\odot$ systems show no discernable spiral structure. The disk around the 2 $M_\odot$ star displays clear signatures of gravitational instability, characterized by a prominent large-scale two-armed spiral. Disks around higher stellar mass stars also develop spiral structure, but do not appear in the same low-mode configuration as the 2 $M_\odot$ case.

- The strength of the gravitational instability is quantified by the maximum perturbation amplitude in the disk density. Larger perturbations correspond to stronger density contrasts, typically associated with spiral structure.
- Figures 1 and 2 both show the maximum perturbation amplitude increases with host stellar mass up to 2 $M_\odot$ followed by an overall decreasing trend at higher masses.
- Figure 3 shows column density plots consistent with this behavior:
  - 0.5-1$M_\odot$: No discernible spiral structure
  - 2$M_\odot$: Prominent large-scale two-armed spiral
  - 3-3.5$M_\odot$: Reduced large-scale spiral structure

Discussion

- Initially, as the system mass increases, the disk becomes more susceptible to GI.
- Although stellar irradiation has been shown to suppress GI, it is insufficient to do so around lower-mass stars.
- Beyond 2 $M_\odot$, the effects of stellar irradiation become relevant, and GI is suppressed again
- Some agreement with observations showing a peak in occurrence of massive planets (like those formed by fragmentation) around stars with mass $M{\sim}1.68\ M_\odot$[7], but discrepancy in peak worth investigating.