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Global simulation of thermal torques

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ABSTRACT

1. INTRODUCTION

We follow up Hankla et al. (2020) :)

2. METHODS

2.1. *Disk model*

Isentropic disk model from Fung et al. (2017). The simulations are performed in spherical coordinates, where r, ϕ, and θ denote the usual radial, azimuthal, and polar coordinates, respectively.

$$\Phi = -\frac{G(M_* + M_p)}{1+q}\Bigg[\frac{1}{r} + \frac{q}{\sqrt{r^2 + R_p^2 - 2rR_p\cos\phi' + \epsilon^2}} - \frac{qR\cos\phi'}{R_p^2}\Bigg] \tag{1}$$

In eq. 1, $q = M_p/M_*$ is the mass ratio of a protoplanet to a star, ϵ is the smoothing length of the planet's potential, and $\phi' = \phi - \phi_p$ denotes the azimuthal separation from the planet. $GM = 1$, $R_p = 1$.

Keplerian velocity $v_k = \sqrt{\frac{GM}{r}}$ and keplerian frequency $\Omega_k = \sqrt{\frac{GM}{r^3}}$ equal to 1 at the planet's orbit.

v_p - planet's orbital speed. $q = 1.5 \times 10^{-5} \approx 5M_{\oplus}$

The planet is introduced to the disk gradually, where its mass increases to the desired value over the first orbit.

The simulation domain spans $0.65R_p$ to $1.35R_p$ in the radial, and the full 2π in azimuth.

The Hill radius of a planet is:

$$r_H = R_p\left(\frac{q}{3}\right)^{\frac{1}{3}} \tag{2}$$

r_s is a small fraction of r_H, between 3% to 10% of r_H.

The isentropic equation of state:

$$p = \frac{c_0^2\rho_0}{\gamma}\left(\frac{\rho}{\rho_0}\right)^{\gamma} \tag{3}$$

In Eq. 3, c_0 is the isothermal sound speed when $\rho = \rho_0 = 1$. The disk's scale height $H = 0.05$ scales the sound speed as $c_0 = H\Omega = 0.05$.

2.1.1. *Initial conditions*

For hydrostatic equilibrium:

$$\rho = \rho_0\Bigg[\left(\frac{R}{R_p}\right)^{(-\beta+\frac{3}{2})\frac{2(\gamma-1)}{\gamma+1}} - \frac{GM(\gamma-1)}{c_0^2}\left(\frac{1}{R} - \frac{1}{r}\right)\Bigg]^{\frac{1}{\gamma-1}} \tag{4}$$

$\beta = \frac{3}{2}$ defines the surface density profile $\Sigma \propto R^{-\beta}$.

The orbital frequency of the disk:

$$\Omega = \sqrt{\Omega_k^2 + \frac{1}{r\rho}\frac{\partial P}{\partial r}} \tag{5}$$

$$v_r = v_\theta = 0$$

2.1.2. *Resolution*

We tried two different sets of resolutions with two different static mesh refinement (SMR) levels around the location of a planet: SMR2 (for SMR level $l = 2$) and SMR3 (for SMR level $l = 3$).

The resolution for non-refined disk is $[192, 80, 384]$ cells for r-,θ-, and ϕ-directions, and the sizes of one cell in r-,θ-, and ϕ-directions are $[3.65 \times 10^{-3} r_p, 3.75 \times 10^{-3}, 1.6 \times 10^{-2}]$.

I increased the resolution in the following regions: $0.9 - 1.1r_p$ in r-direction, $87^o - 93^o$ in θ-direction, and $177^o - 183^o$ in ϕ-direction. The resolution for refined disk with level $l = 3$ is $[360(222 + 69 + 69), 160(106 + 67 + 67), 410(24 + 193 + 193)]$ cells for r-,θ-, and ϕ-directions, and the sizes of one refined cell in r-,θ-, and ϕ-directions are $[9 \times 10^{-4} r_p, 9.36 \times 10^{-4}, 4 \times 10^{-3}]$. Look at the Figure 1 to see the comparison of the total torques for different levels of refinement.

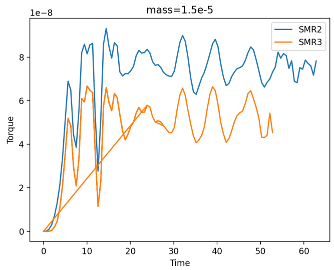

Figure 1. The comparison between the torques.

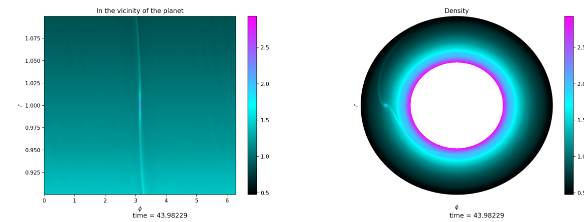

Figure 2. The density profile of the disk with a perturber with SMR level $l = 3$ at the 7th global orbit.

2.2. *Energy injection and transport*

I injected the energy of value $L_c = 24 \times 10^{-11}$ (times the time) into the sphere of radius $0.003 r_p$ (8 cells) around the planet location.

The thermal diffusivity is $\chi = 0.00013 H^2 \Omega$ with $\lambda_c = 0.5 r_p$. The Eq. 6 is taken from the Eq. 17 in Hankla et al. (2020). Look at the Figure 2 to see how the disk looks like with these parameters (including the thermal diffusivity).

$$\chi = \frac{3\lambda_c^2 \gamma \Omega_0}{8\pi^2} \tag{6}$$

2.3. *Athena++ simulations*

3. RESULTS

4. DISCUSSION

REFERENCES

Fung, J., Masset, F., Lega, E., & Velasco, D. 2017, The Astronomical Journal, 153, 124, doi: 10.3847/1538-3881/153/3/124

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