Forming satellites early on: accretion onto circumplanetary disks

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Circumplanetary disks (CPDs), of which the disk in the PDS 70 system is the first directly observed example, play a crucial role in the accretion of material onto planets, as well as in the formation of their satellite systems. By studying the properties of CPDs, we can gain insight into the role they play in shaping the Solar System and other planetary systems. In our work, we developed high-resolution 3D hydrodynamical simulations with Athena++ to study angular momentum accretion onto CPDs. Angular momentum accretion onto CPDs determines the overall long-term disk evolution, and helps us understand the accretion of dust that creates planetary satellites.

Simulation details:

- ☑ spherical-polar coordinates
- ☑ global 3D
- ☑ nested static mesh refinement
- ☑ here: Jupiter-mass planet

☑ **polytropic equation of state**

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

☑ **isentropic disk profile**

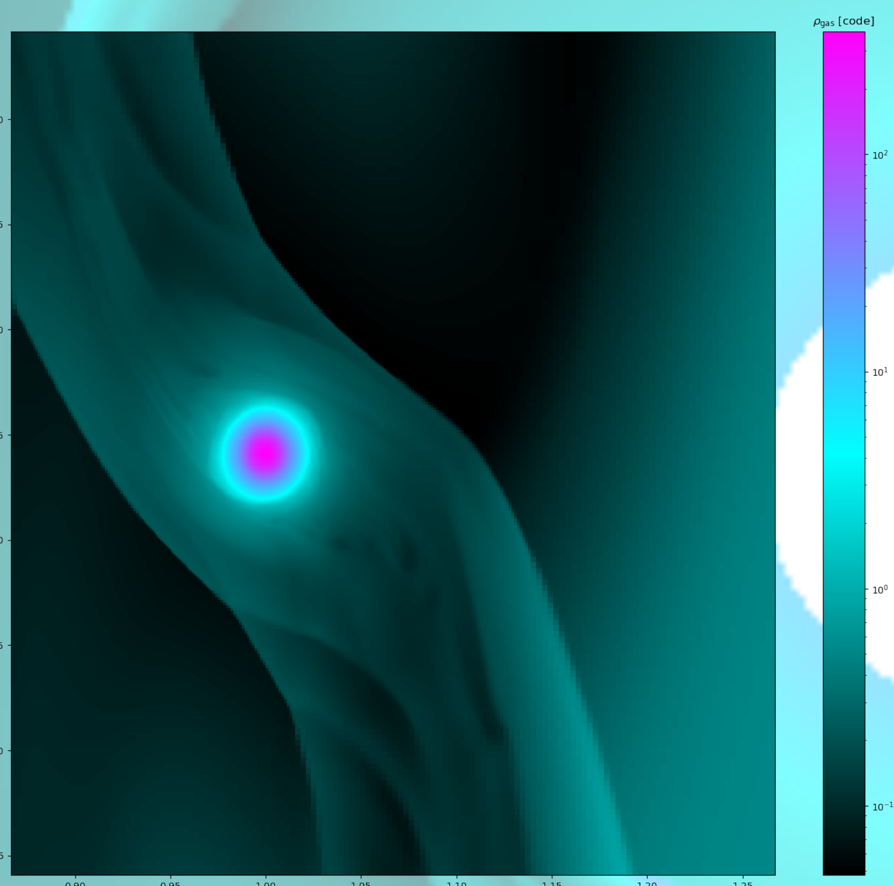
$$\rho = \rho_0\left[\left(\frac{R}{R_p}\right)^{(-\beta+\frac{3}{2})\frac{2(\gamma-1)}{\gamma+1}} - \frac{GM(\gamma-1)}{c_0^2}\left(\frac{1}{R}-\frac{1}{r}\right)\right]^{\frac{1}{\gamma-1}}$$

normalization units and corresponding values

Quantity	Unit
Length	r_p
Velocity	v_{K0}
Time	r_p/v_{K0}
Density	ρ_0
Pressure	$\rho_0 v_{K0}^2$
Mass accretion rate	$\rho_0 r_p^2 v_{K0}$

regions of all three refinement levels

Refinement #1	$9\pi/20 \rightarrow 11\pi/20$	θ
	$0.8 \rightarrow 1.2$	r
	± 0.2	ϕ
Refinement #2	$19\pi/40 \rightarrow 21\pi/40$	θ
	$0.9 \rightarrow 1.1$	r
	± 0.1	ϕ
Refinement #3	$39\pi/80 \rightarrow 41\pi/80$	θ
	$0.95 \rightarrow 1.05$	r
	± 0.05	ϕ



Preliminary Athena++ simulations of a (single) giant planet interacting with a protoplanetary disk, shown at an early time when co-orbital gas is still present. The global simulations are in 3D, to capture properly the flow of gas across the gap, and use multiple levels of static mesh refinement to efficiently resolve has near the planet that contributes to the migration torque.

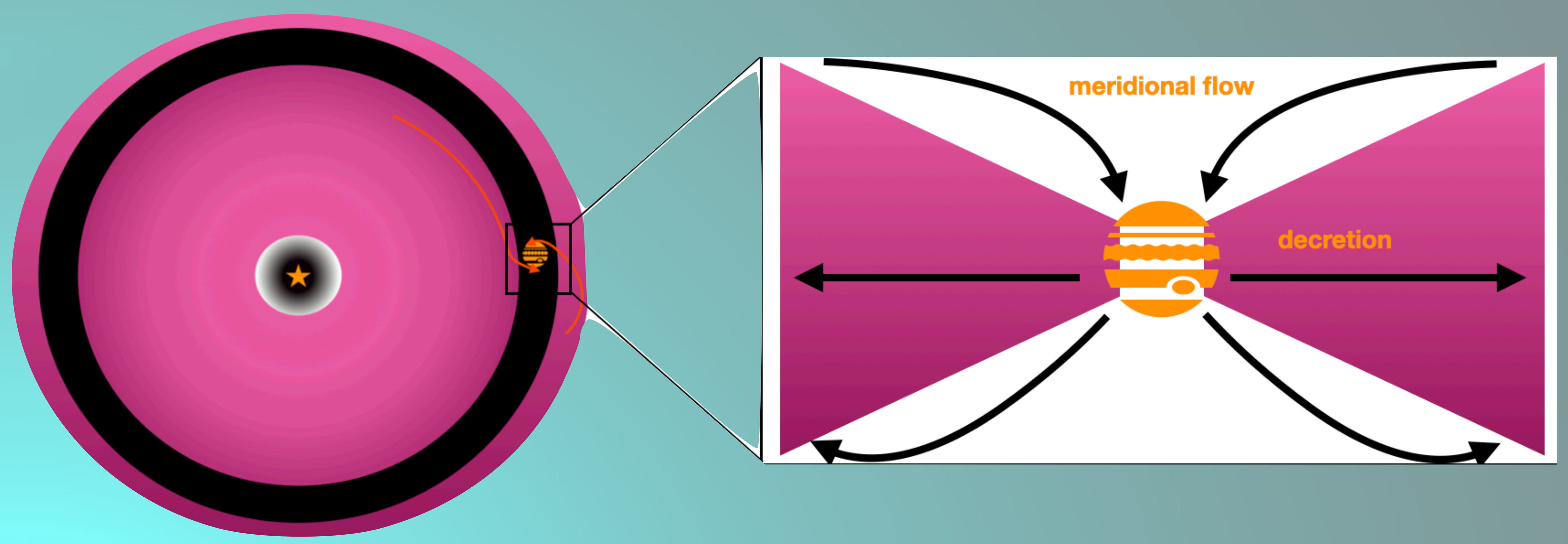
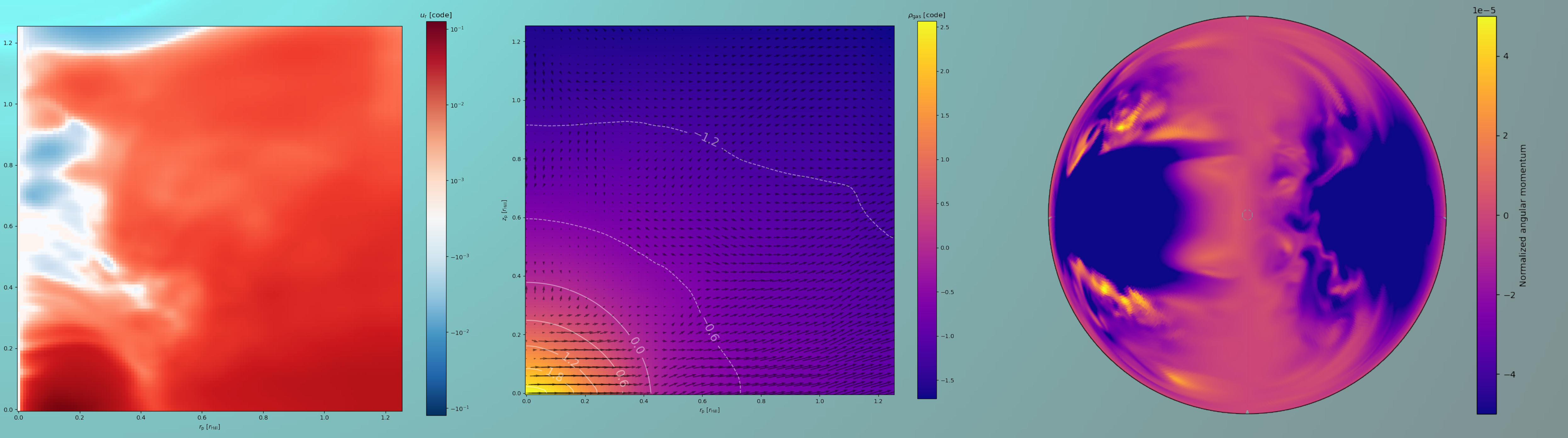


Illustration of the meridional flow around a circiplanetary disk. Here, the planet has already cleared out a gap. As a result, there is a continuous circulation of gas within the region. The gas flows both in a circular motion around the planet and outflows radially. The material is raining down on top of the planet at free fall, and due to conservation of angular momentum, it spins up creating a CPD which then viscously decretes down to the protoplanetary disk. It is important to study this circularization and accretion in order to understand how the satellite-forming material gets into the CPD and remains there.



a) azimuthally-averaged radial velocity; b) azimuthally-averaged density; c) normalized angular momentum flowing onto the Hill sphere of the planet. The coordinates of the first two plots are cylindrical, planetocentric, so that the planet is in the left-bottom corner of each figure.

Prior hydrodynamic studies have shown that the gas flow onto the CPD is three-dimensional, with vertical gas inflow into the CPD, while outflow can be primarily equatorial along the midplane of the disk. It is challenging to produce high-resolution global disk simulations to resolve the CPD properly. In this work, we are using nested mesh simulations with an isentropic equation of state to study angular momentum accretion onto the CPD as a function of planetary mass and disk properties. The use of static mesh refinement (SMR) allows us to substantially increase the resolution around the location of the planet while keeping the resolution in the rest of the protoplanetary disk relatively low.

References:

Batygin, K., Morbidelli, A. 2020, ApJ, 894, 2, doi: 10.3847/1538-4357/ab8937