Spirals and Warps
Non-axisymmetric Features in Protoplanetary Disks

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Introduction

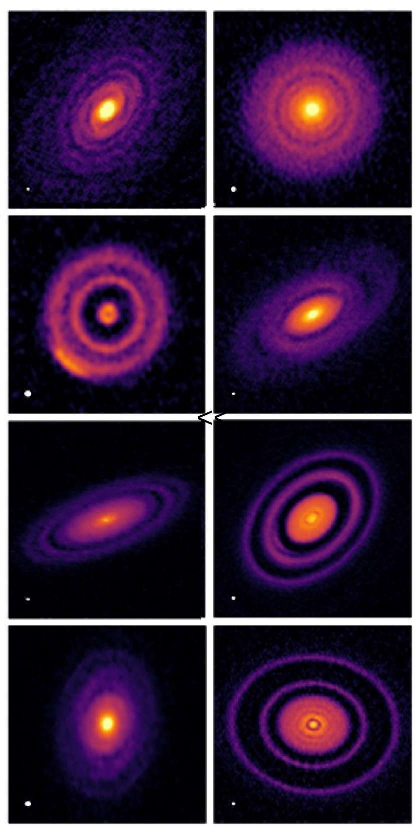

Fig. 1: Observations of the DSHARP probramm. (Andrews et al. 2018)

As more and more observations of protoplanetary disks are presented, a significant fraction of them shows non-axisymmetric features. In this work, we focus on regions that appear darker than the rest ofthe disk. These regions are often suspected to be caused by a misaligned inner disk region casting a shadow. Disks with a misaligned inner region are called warped disks. As the warp in a disk evolves in time, the shadows may change their appearance. Therefore, we aim to simulate the evolution of the warp in 3D hydrodynamic simulations, as well as a potential warp formation scenarios: a stellar flyby gravitationally influencing the disk geometry.

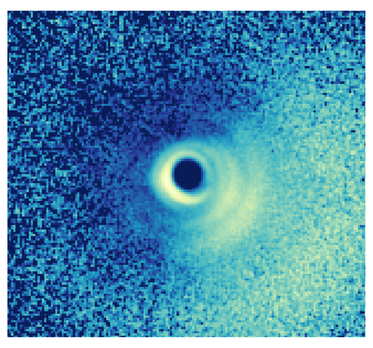

Fig. 2: HD 139614 (Muro-Arena et al. 2020)

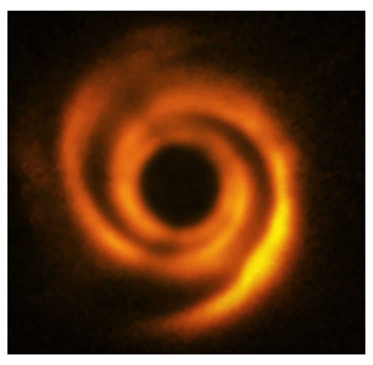

Fig. 3: HD 135344B (ESO, Stolker et al. 2016)

Setup

We perform three-dimensional hydrodynamic simulations using FARGO3D (*Benítez-Llambay & Masset 2016*) in a spherical coordinate system (see Figure 5).

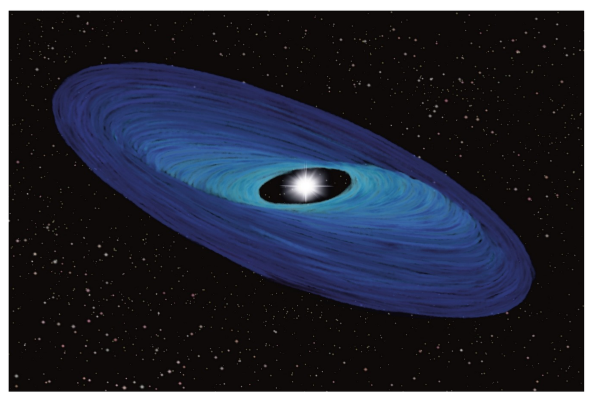

Fig. 4: Warped disk (artist's impression)

Question: Is it possible to model warped disks in a grid-based hydrodynamics code?

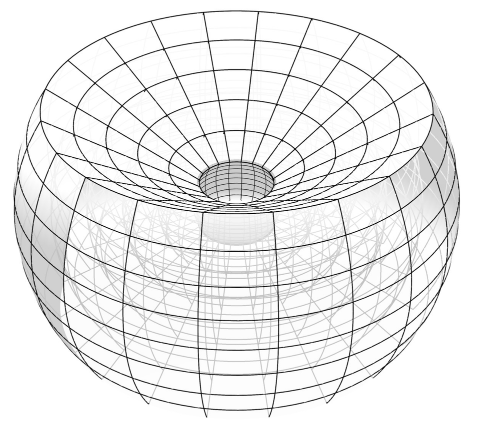

Fig. 5: Spherical coordinate system with a conical cutout north and south to save computation time.

We carefully test grid effects such as numerical friction by setting up a planar disk that is tilted with respect to the coordinate system's equatorial plane. We find the resolution in θ (z-direction) to be most important, as it traces the up-and-down movement of a gas parcel during an orbit. A low resolution in θ leads to precession of the disk, while a sufficiently high θ-resolution ensures that the grid effects are small.

Results

We set up an initially warped disk without any external torques to sustain the warp. The disk has a viscosity of $\alpha=10^{-3}$. Our setup is situated in the wave-like regime of warp evolution. The warp therefore travels as a wave through the disk, as shown in Figure 6.

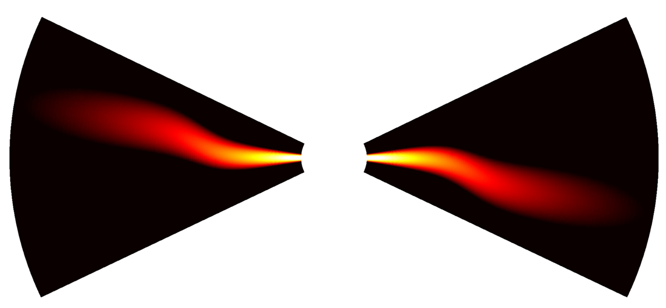

Fig. 7: Vertical slice of the initial warp setup in FARGO3D.

Compared to smoothed particle hydrodynamics (SPH), a grid-based code allows us to model lower viscosities and achieve a better resolution in low density regions, particularly at the surface of the disk.

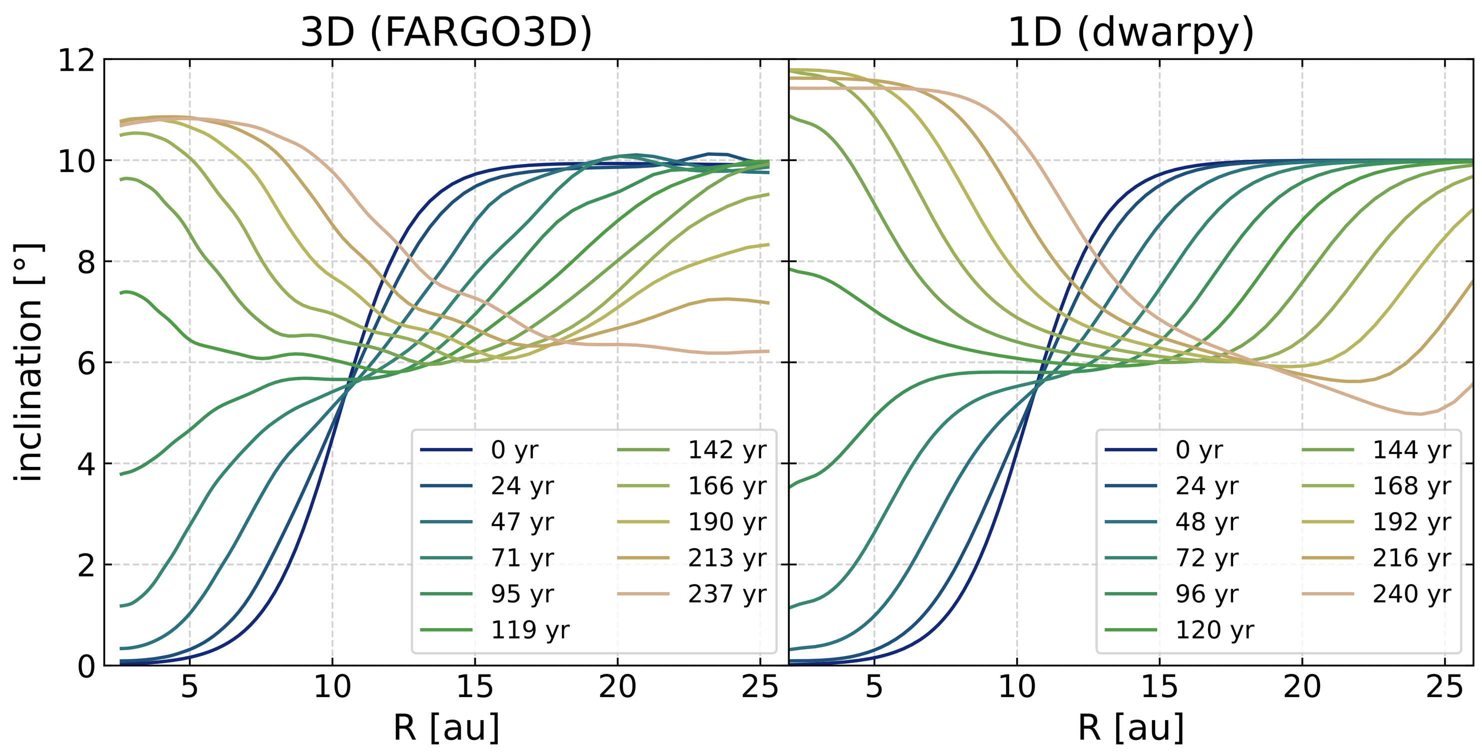

Fig. 6: Warp evolution in a 3D hydrodynamic simulation (left panel) and in a 1D ring code (right panel). The inclination is defined as the angle between angular momentum vector and z-axis.

The warp evolves in time because of the misalignment of neigboring orbital planes. This misalignment causes internal torques, because neighboring gas parcels have to perform a slight vertical oscillation with respect to each other. On longer time scales these internal torques act to smooth out the warp to a planar disk. Note that it ends up tilted in space due to angular momentum conservation.

We compare the results of the 3D simulation to a simulation made using the 1D ring code *dwarpy*. In this setup, the disk is represented in a one-dimensional way by splitting up the disk into concentric annuli (see Figure 8). The plane of each annulus is determined by the angular momentum vector, which can be updated according to the evolution equations by *Dullemond, Kimmig & Zanazzi 2022*. This equation set was first introduced by *Lubow & Ogilvie* 2000 and later expanded by *Martin et al. 2019*.

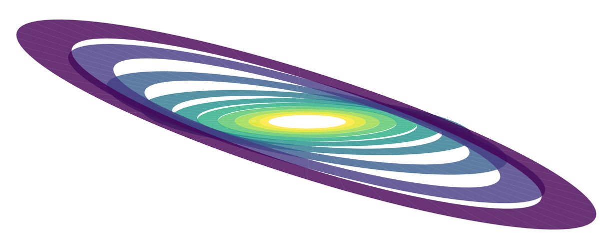

Fig. 8: Concentric annulus setup in a 1D simulation of a warped disk in *dwarpy*.

Simulation of a Flyby

We conduct simulations of a stellar flyby in order to investigate a possible formation scenario for warped disks. In our setup, the flyby trajectory is inclined by 30° with respect to the disk plane. The closest approach is in the plane of the disk, with a distance of 52 au from the central star. The disk extents to 26 au. We find that the flyby excites spirals and a warp, as shown in Figure 10.

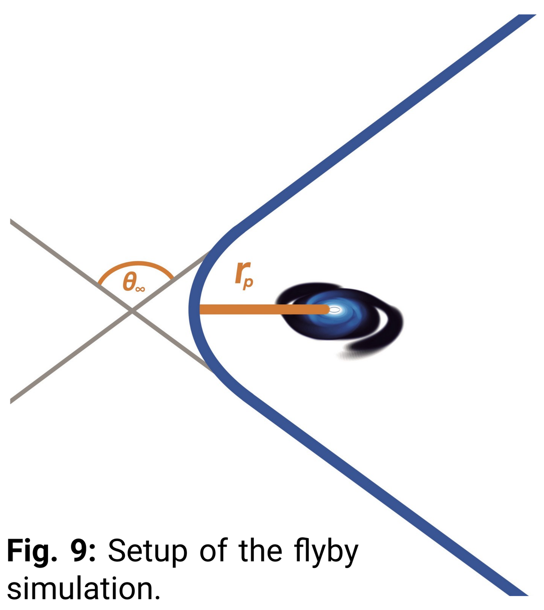

Fig. 9: Setup of the flyby simulation.

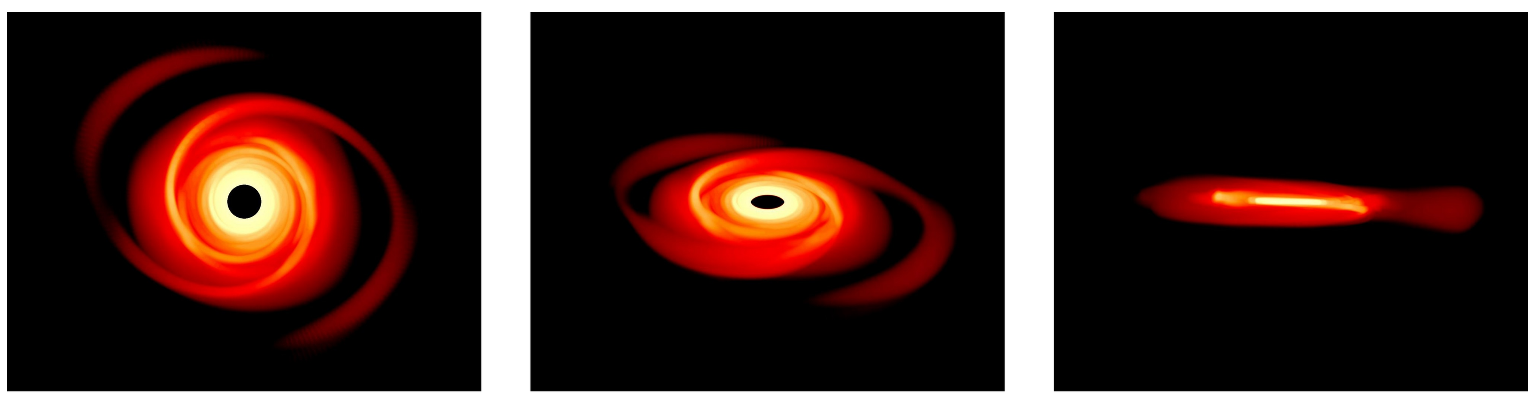

Fig. 10: 3D simulation of the flyby during the close encounter seen from three different angles.

Conclusion

In this work, we investigate warped disks in FARGO3D, a grid-based code. Testing the grid effects, we find that the resolution in θ plays an important role and needs to be set sufficiently high.

Comparing a full hydrodynamic 3D simulation to the 1D evolution description shows a very similar warp evolution in both setups.

A stellar flyby can warp the disk by a few degrees, while also exciting spirals. To assess the parameters determining the warp properties, we plan to perform further flyby simulations with different geometries.

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