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Hydrodynamics Group

A 3D Numerical Study of Gravitational Instabilities in Young Circumbinary Disks

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Abstract

Gravitational instabilities (GIs) in protoplanetary disks have been suggested as one of the major formation mechanisms of giant planets. Theoretical and computational studies have indicated that certain family of GIs can be excited in a circumbinary disk, which could lead to enhanced protoplanet formation [1, 2]. We have carried out a 3D simulation of a gravitationally unstable circumbinary disk around a young Sun-like star and a 0.02-$M_\odot$ companion, both inside the central hole of the disk. Here we present a preliminary comparison between this simulation and a similarly simulated circumstellar disk around a solar-mass star but without the low-mass companion. The GIs stimulated by the binary and those that arise spontaneously are quite different in structure and strength. However, no fragmentation is observed, even after many orbital periods as measured in the outer disk.

Simulations

We conduct our disk simulations using the Indiana University 3D Hydrodynamics Group (IUHG) code [3, 4]. The initial 2D model for the simulations has a central star of 1 $M_\odot$ and a nearly Keplerian disk of 0.14 $M_\odot$, with surface density $\Sigma(r) \propto r^{-0.5}$ from 5 AU to 40 AU. A brown dwarf companion of 0.02 $M_\odot$ at r = 2.5 AU is added into the central hole of the disk, turning the disk into a circumbinary disk. This model is then loaded into our IUHG code which solves the 3D hydrodynamics equations in conservative form on a cylindrical grid of uniform spacing with an initial r,ϕ,z-resolution of (256,512,32) and reflection symmetry about z = 0. The gravitational interactions between the protostar, the brown dwarf, and the disk are handled by including indirect potentials in the hydrodynamic calculations ([see [5]). Instead of assuming γ = 5/3 or 7/5, a more realistic equation of state is employed where γ is calculated based on the local temperature in each cell [6]. Here we adopt the treatment of radiative physics described in Boley et al. (2007, [7]). The opacities and molecular weights used in our simulations are described in D'Alessio et al. [8]. For comparison, a fiducial disk simulation presented a few years ago (see [9]) is also included here. It has identical parameters as described above, except that there is no companion inside the central hole of the disk. In both simulations, the grid cells were doubled soon after the development of GIs in both r and z directions to accommodate the expansion of the disk.

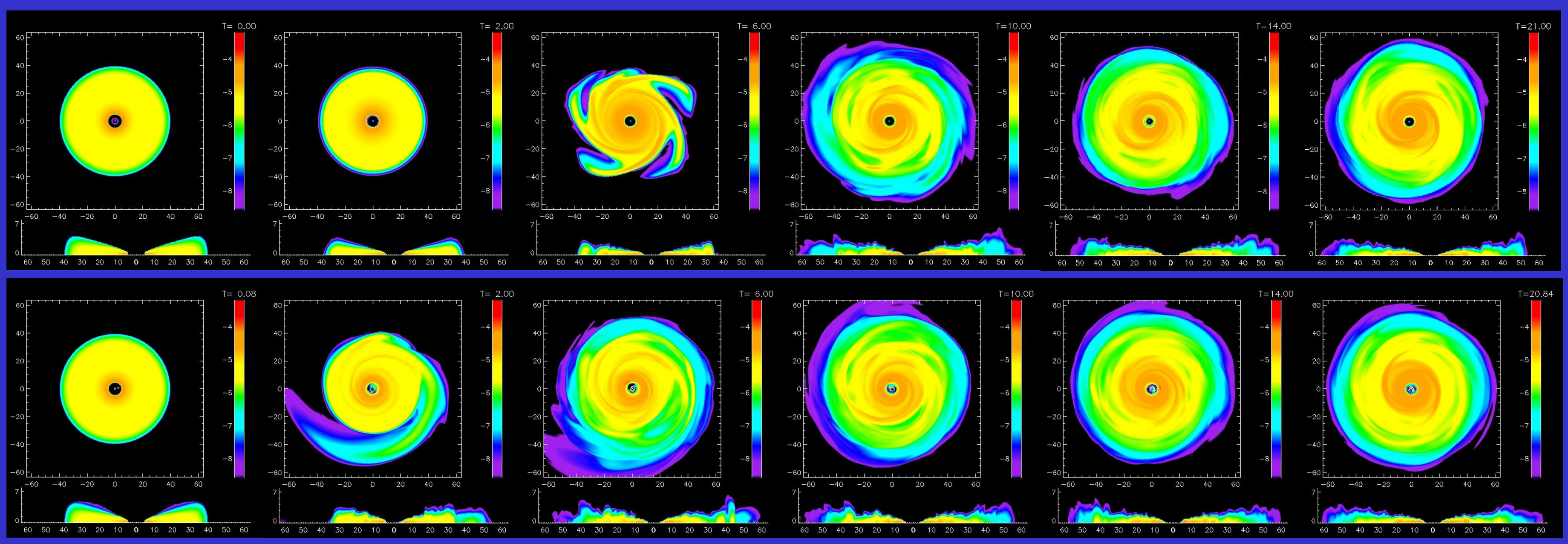

Figure 1: Snapshots of midplane and meridian density maps at various times (shown in ORPs at the upper right corner of each image) for the fiducial disk on the upper row and for the circumbinary disk on the lower row. The numbers on the axes are given in units of AU. Densities are displayed on a logarithmic color scale shown on the right of each image. **A movie of the circumbinary run can be found at: https://iu.box.com/shared/static/s2l0pyijrwpsq3171nbi.mpg**

Results

Like the disks we have studied before (e.g., [9],[10]), both disks go through an initial burst phase, following the applied perturbations. Then, at around 14 ORPs, the disks settle into a quasi-steady asymptotic phase of GI activity. Here a ORP is defined as the initial outer rotation period at 33 AU, which is about 180 years. We believe that the disk behavior during this asymptotic phase is independent of the particular initial conditions, so we focus our analysis on this time period (see [4], [9], [10]).

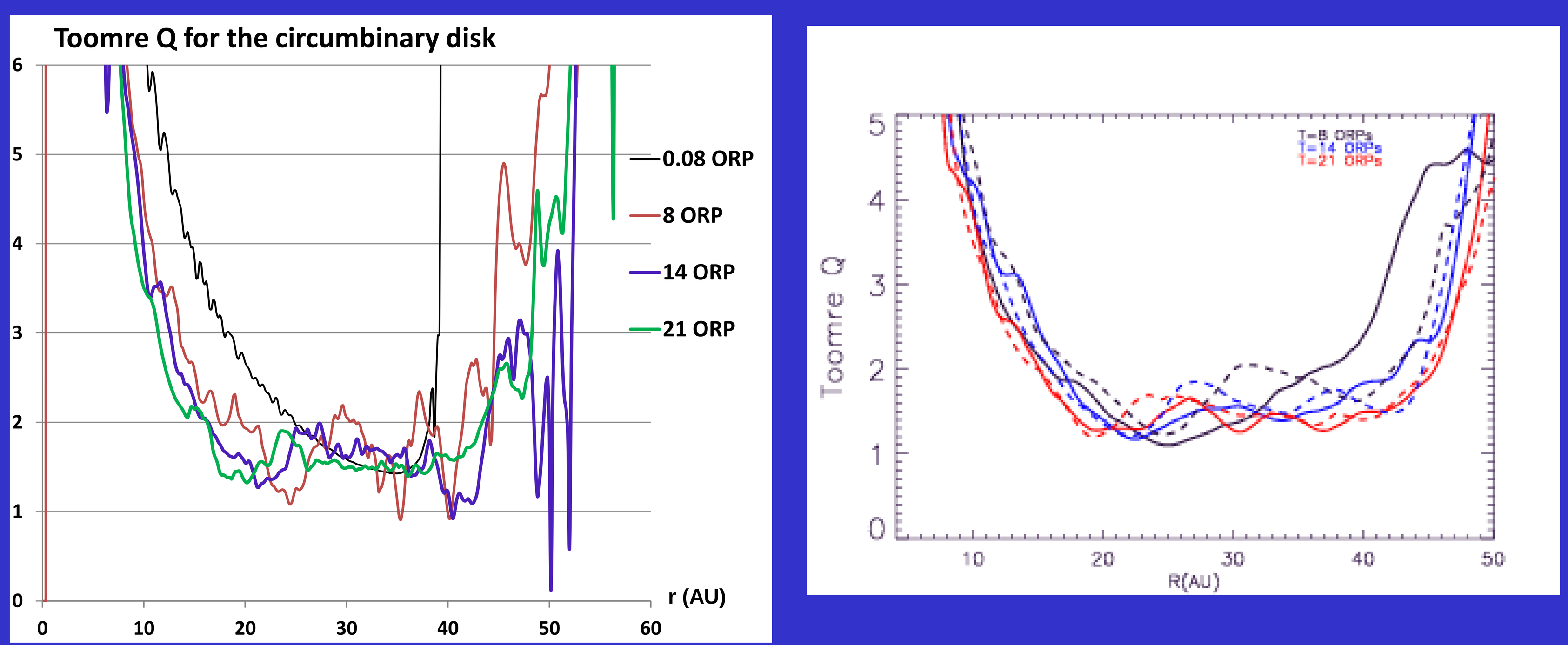

Figure 2: Radial distribution of Toomre Q (= $c_s\kappa/\pi G\Sigma$) at various times for the circumbinary disk alone (left) and the two disks compared (right). These Q values are computed at the disk midplane.

Results

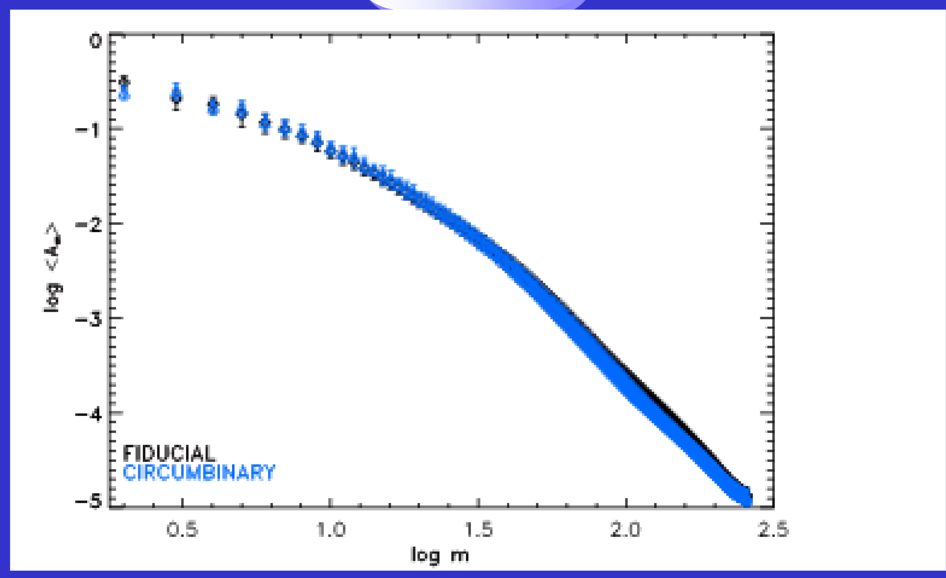

Figure 3: <Am> vs. m averaged over the asymptotic phase (14 to 21 ORPs) for both disks.

Fourier amplitudes A_m for the nonaxisymmetric structure in the disk are defined as [10, 11]

$$A_m = \frac{\int \rho_m r dr dz}{\int \rho_0 r dr dz}$$

where ρ_0 is the axisymmetric component of density and ρ_m is the amplitude of the mth Fourier component of the density in the azimuthal direction. Time-averaged A_m's between 14 and 21 ORPs are plotted in Figure 3 against m. As a result of these nonaxisymmetris, both disks showed substantial mass transport and redistribution. The average mass transport rates are computed and shown in Figure 4 below.

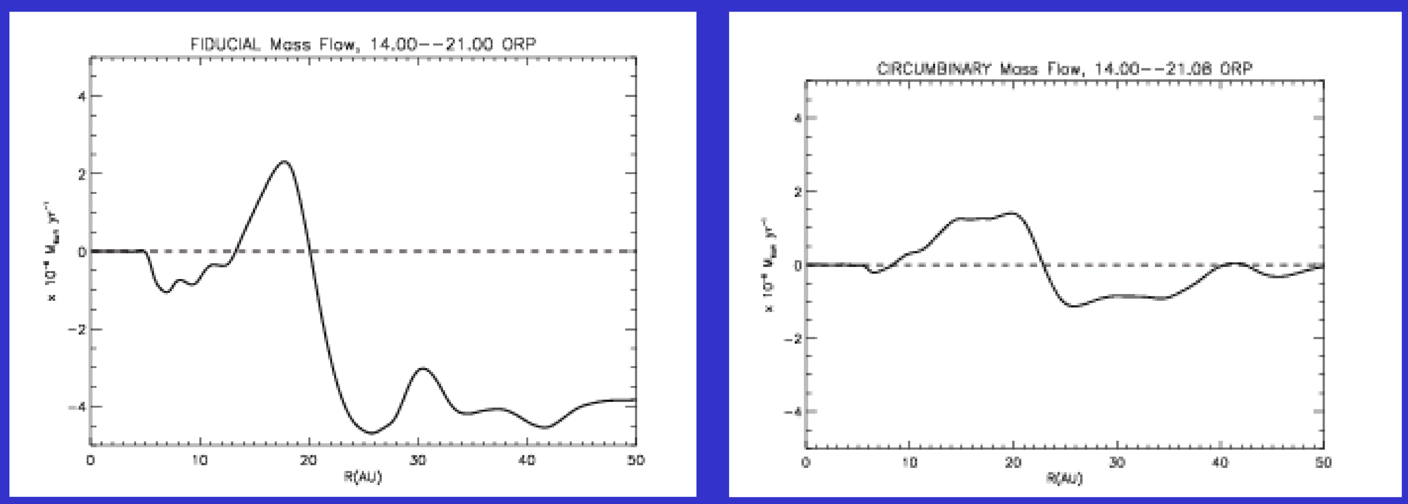

Figure 4: The mass inflow/outflow rates calculated by differences in the total mass fraction as a function of radius, averaged over the asymptotic phase (14 to 21 ORPs).

As a result of the interaction with the disk, the orbital eccentricity of the brown dwarf companion (as measured in the star's reference frame) has gone from 0.018 initially to about 0.040 by the end of the 21 ORPs of simulation. Little change in a is observed.

Preliminary Conclusions

1) This data analysis and comparison is ongoing progress; to obtain a complete picture of the effect of the binary companion on the disk instabilities, we plan to do more analysis on torques driven by the orbital motion of the binary system.

2) While the presence of the substellar companion seems to affect the onset of GIs, it appears that the bulk of the disk relaxes into essentially the same quasi-steady state as the disk without a companion. There is sustained mass transport by GIs but no fragmentation. There may be some effects in the inner disk which need to be examined further.

3) More simulations of GIs in circumbinary disks are needed to explore the huge parameter space in terms of the mass of the binary companion, the orbital separation, etc.

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