Vortices being killed by planets in thermal relaxed disks

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Abstract

Observed vortices in disks have recently been associated with planets, e.g. that the vortex has formed in the pressure maxima at the outer edge of the gap in the disk created by the planet. Here we show that the mechanism that can create vortices in radial stratified accretion disks - the disk needs to be buoyantly unstable in the radial direction and have a thermal relaxation in the order of one orbital period - will here damp the vortex, because the outer wall of a gap is buoyantly stable. When pressure and entropy radially decrease, or more generaly the entropy and pressure gradient have the same sign, then vortices can get amplified. But in the case of a gap rim pressure increases, while entropy decreases, thus the stratification is stable. We show in analytical arguments and by numerical simulations, that the detection of a vortex is a good argument that inside this structure there is no planet.

The problem

Observational evidence

ALMA observations of the disk around the star Oph IRS 48 detected a highly asymmetric concentration of milimeter–sized dust grains [1]. They argue this can be modeled by dust trapping in a large anticyclonic vortex. CO line observations of this system showed the presence of a central cavity, which was explained as being a gap opened by a high mass planet [2].

Numerical experiments

We know that vortices can be created in disks due to the baroclinic instability [3]. Studies of the baroclinic vortex amplification showed that thermal relaxation has a crucial relevance for vortex growth [4, 5]. A parameter study of the baroclinic vortex amplification pointed out that vortices can grow in disks with entropy gradients expected for protoplanetary disks [6].

The question

Thereby, the question we want to address in this work is how planets and vortices are related in protoplanetary disks with thermal relaxation.

Simulations

We performed global hydrodynamical simulations of radial stratified protoplanetary disks using the PLUTO code [7] and the planet–disk approach presented in [8], but considering thermal relaxation.

Numerical setup

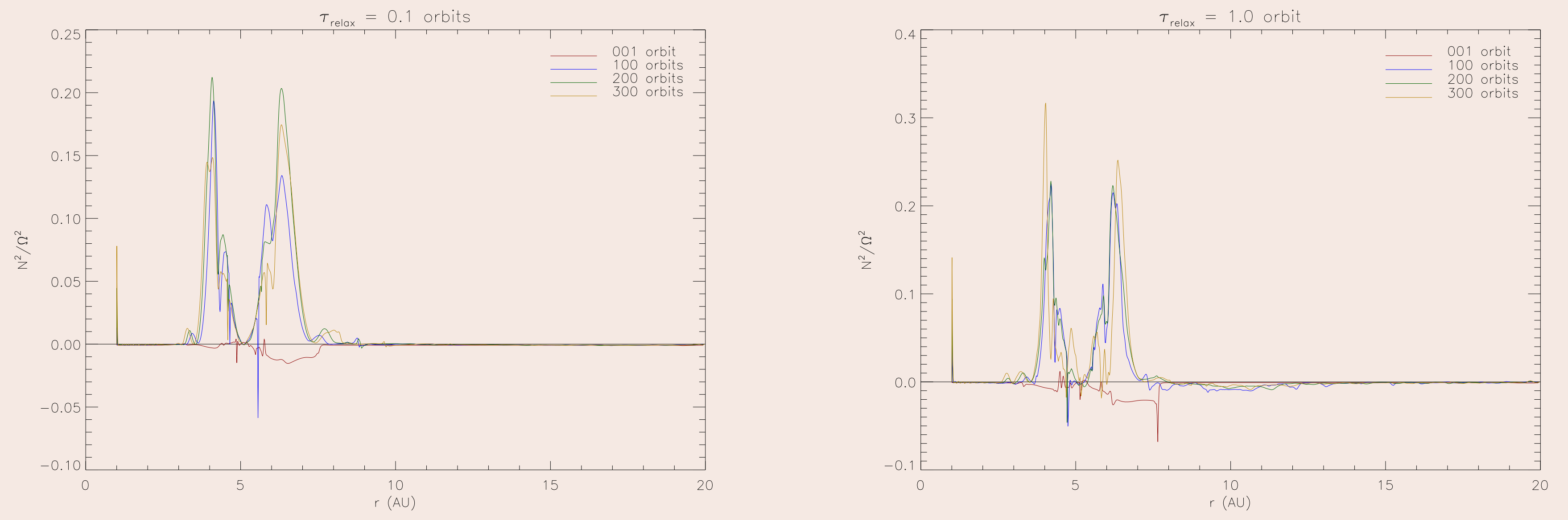
- 2D in polar coordinates;
- Resolution of 1024x1024 grid cells;
- Stationary solution of a sub–Keplerian disk as initial conditions;
- Integration intervals
  - $r = [1, 20]$ AU
  - $\phi = [0, 2\pi]$
  - 300 orbits;
- Jupiter-like planet ($m_p/m_s = 10^{-3}$) at Jupiter's location ($r_p = 5.2$ AU);
- $\tau_{relax} = [0.1, 1.0, 2.0, 5.0, 10.0]$ orbits.

Disk stability

We can quantify the radial stability in a disk through the Brunt–Väisälä frequency (N), which is given by [6]

$$N^2 = -\beta_p \beta_S \frac{1}{\gamma}\left(\frac{H}{r}\right)^2 \Omega^2,$$

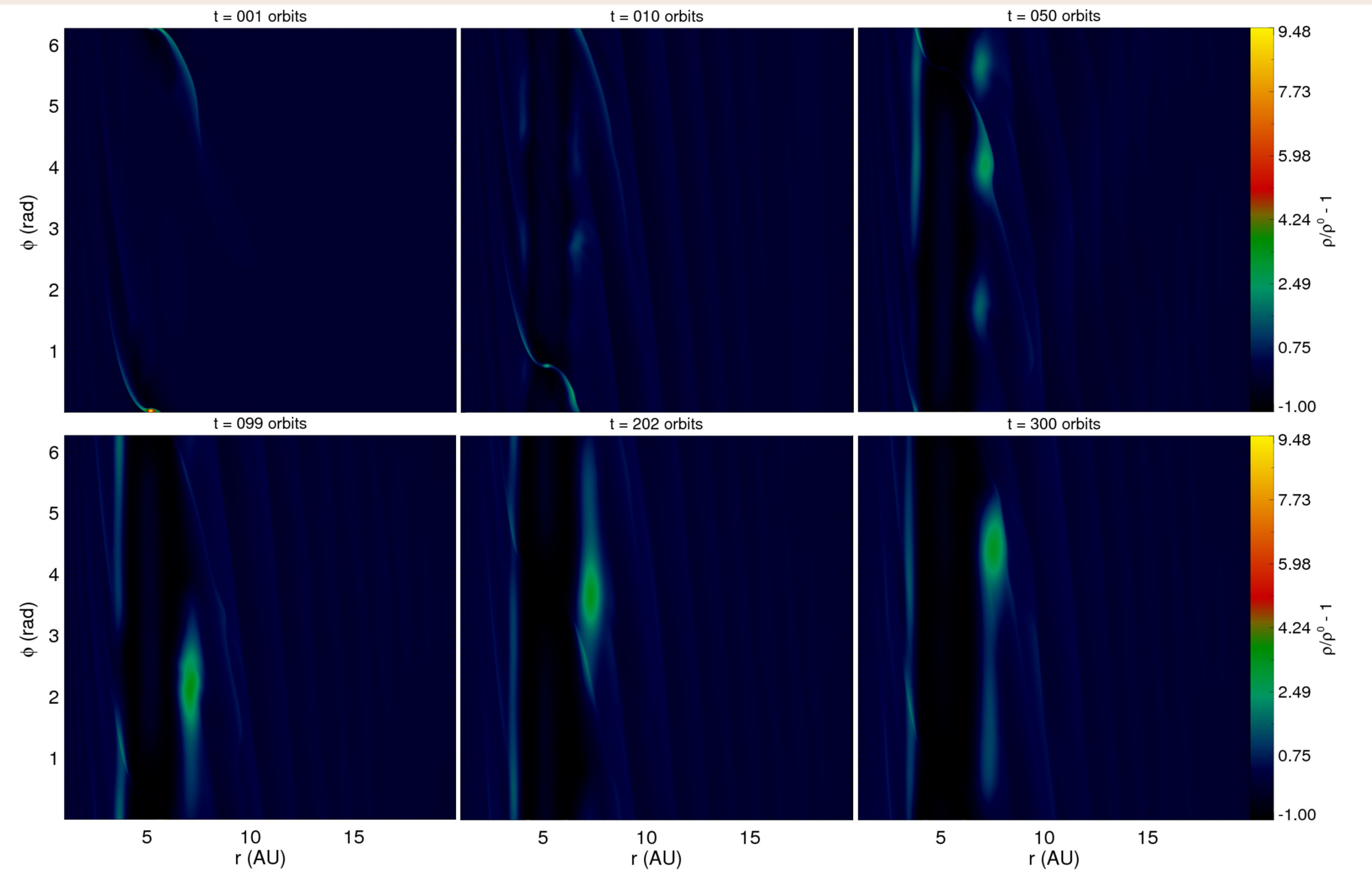
where β_p is the pressure gradient, β_S the entropy gradient, γ the adiabatic index, H the pressure scale high, r the radii and Ω the Keplerian angular velocity.
Positive values of N^2 indicate a stable situation, while negative values mean instability.



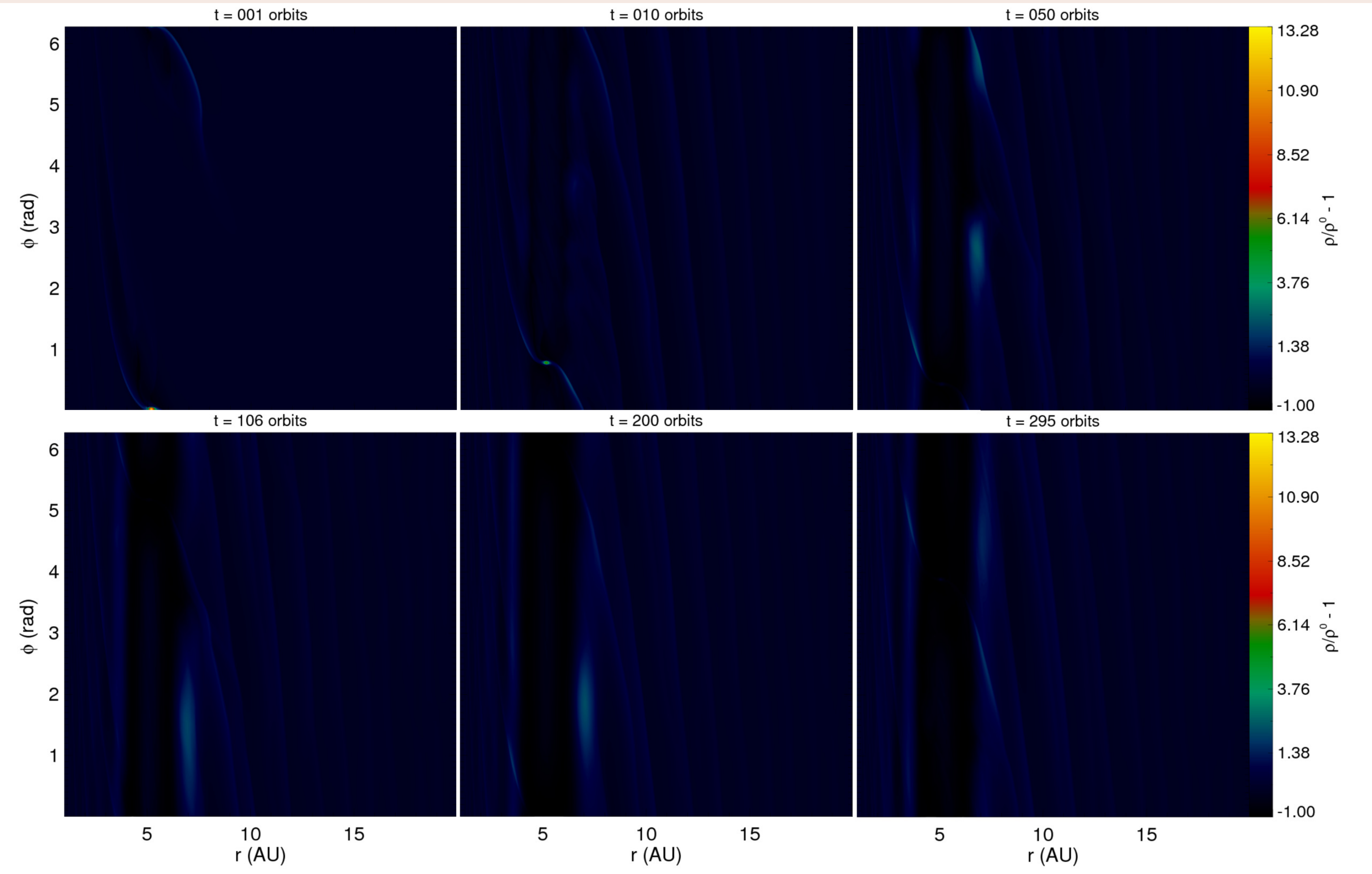
The plot on the left side shows N^2/Ω^2 for $\tau_{relax} = 0.1$ orbits and on the right for $\tau_{relax} = 1.0$ orbit. For both cases we made an average in azimuth. On the beginning of the simulation the disk is buoyantly unstable around the planet location, thus we have vortex formation and amplification. After we have gap opening, we can see that the inner and outer wall of this gap became buoyantly stable.

We showed here the two most extreme cases. The major difference among them is the relaxation time scale. Just for τ_{relax} around one orbital period, we can observe the damping of vortices.

Density evolution



The panel above shows the density evolution for $\tau_{relax} = 0.1$ orbits. We can observe the formation of vortices at the outer edge of the gap after few planet orbits. Those vortices gather together and form a bigger one, which survives until the end of the simulation.



The panel above shows the density evolution for $\tau_{relax} = 1.0$ orbit. We can observe the formation of weak vortices at the outer edge of the gap, also after few planet orbits. Those vortices gather together in the same way as before, but in contrast to the previous case, the final vortex get damped along the simulation interval.

$\tau_{relax} = 2.0$ orbits shows a similar behavior to $\tau_{relax} = 1.0$ orbit. For the other cases, we observed again the formation and maintenance of vortices.

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