# How does a vortex trap a planet?

S. Ataiee*[1], C.P. Dullemond[2], W. Kley[3], and Zs. Regály[4]

[1] *School of Astronomy, Institute for Research in Fundamental Sciences (IPM),Tehran, Iran*
[2] *Heidelberg University, Center for Astronomy, Institute for Theoretical Astrophysics, Heidelberg, Germany*
[3] *Institut für Astronomie & Astrophysik, Universität Tübingen, Tübingen, Germany*
[4] *Konkoly Observatory, Research Center for Astronomy and Earth Science, Hungarian Academy of Sciences, Hungary*

## Abstract

*Anticyclonic vortices are considered as a favourable places for trapping dust and forming planetary embryos. On the other hand, they are massive blobs that can interact gravitationally with the planets in the disc. In this work, we studied how a vortex interacts gravitationally with a planet which migrates toward it or a planet which is created inside the vortex. We performed hydrodynamical simulations of a viscous locally isothermal disc using GFARGO. Using a stationary Gaussian pressure bump in the disc, we formed a large vortex and then, we implanted a low mass planet in the outer disc or inside the vortex and allowed it to migrate. We noticed regardless of the planet's initial position, the planet is finally locked to the vortex. We studied different parameters such as background viscosity, background surface density, mass of the planet and different planet positions. While the trapping time and locking angle of the planet vary for different parameters, the main result, which is the planet-vortex locking, remains valid. We interestingly discovered that even a planet with a mass less than $5\times10^{-7}\mathrm{M}_\star$ comes out from the vortex and is locked to it. This effect can make the vortices a suitable place for continual planet formation if a long-lived large-scale vortex is formed inside a protoplanetary disc.*

Theoretical models suggest that vortices can develop in protoplanetary discs and help solving time scale problems in the early planetary formation process and fast inward migration (e.g. [1, 2, 3]). It has been shown that anticyclonic vortices trap dust particles and boost planet formation (e.g. [4, 5, 6]). The Coriolis force and the resultant higher pressure at the center of anticyclonic vortices help to bring and accumulate the dust particles inside the vortices. On the other hand, anticyclonic vortices behaves as "blobs" of matter and interact with the planets in the disc. It is shown that the torques from the vortices created at the outer edge of a planet-carved gap in weakly viscous discs produce a slight outward migration of the planet [7]. Considering vortices, as either a convenient birth place for planetary embryos or a tool for decrease planetary migration rate, introduces an important question: how does a planet embryo interact with a vortex? If the planet is formed inside a vortex, does it leave its birth place to allow further planetary formation in the vortex or does it stay until it becomes massive enough to open a gap? If a planet is made external

*sareh.ataiee@ipm.ir

Table 1: Models with the parameters we studied. Test models are ones we used to clarify the results. $r_{in}$ and $r_{out}$ are inner and outer boundaries.

| Model | $\nu_{BG}$ | $\Sigma_{BG}$ | $M_p$ | $(\frac{r_{init}}{r_0}, \theta^{\circ}_{init})_P$ | $N_r \times N_s$ | $(r_{in}, r_{out})$ | a |
|---|---|---|---|---|---|---|---|
| Standard | $10^{-5}$ | $5\times10^{-4}$ | $5\times10^{-6}$ | $(1.2, 0)$ | $256\times512$ | (0.5,1.5) | 1 |
| Standard (PinV) | $10^{-5}$ | $5\times10^{-4}$ | $5\times10^{-6}$ | $(1, 80)$ | $256\times512$ | (0.5,1.5) | 1 |
| Viscosity 1 | $10^{-6}$ | $5\times10^{-4}$ | $5\times10^{-6}$ | $(1.2, 0)$ | $256\times512$ | (0.5,1.5) | 1 |
| Viscosity 2 | $10^{-7}$ | $5\times10^{-4}$ | $5\times10^{-6}$ | $(1.2, 0)$ | $256\times512$ | (0.5,1.5) | 1 |
| Density 1 | $10^{-5}$ | $10^{-3}$ | $5\times10^{-6}$ | $(1.2, 0)$ | $256\times512$ | (0.5,1.5) | 1 |
| Density 2 | $10^{-5}$ | $10^{-4}$ | $5\times10^{-6}$ | $(1.2, 0)$ | $256\times512$ | (0.5,1.5) | 1 |
| Planet mass 1 | $10^{-5}$ | $5\times10^{-4}$ | $10^{-6}$ | $(0.99, 359)$ | $512\times1024$ | (0.6,1.4) | 1 |
| Planet mass 2 | $10^{-5}$ | $5\times10^{-4}$ | $5\times10^{-7}$ | $(0.99, 69)$ | $512\times1024$ | (0.7,1.3) | 1 |
| | | | Test models | | | | |
| High-res 1 (HR1) | $10^{-5}$ | $5\times10^{-4}$ | $5\times10^{-6}$ | $(1.2, 0)$ | $576\times1152$ | (0.5,1.5) | 1 |
| High-res 2(HR2) | $10^{-5}$ | $5\times10^{-4}$ | $5\times10^{-6}$ | $(1.1, 0)$ | $576\times1152$ | (0.7,1.3) | 1 |
| Viscosity 1 (fixed-P) | $10^{-6}$ | $5\times10^{-4}$ | $5\times10^{-6}$ | $(1.001534, 0)$ | $256\times512$ | (0.5,1.5) | 1 |

to the vortex but during its migration meets the vortex, does it enter the vortex and disturb the planetary formation process?

Performing locally 2D hydrodynamical simulations by the GFARGO code, we tried to answer the above questions. We produced a long-lived vortex by help of a (semi-)steady Gaussian pressure bump, implanted a low-mass planet in the disc at different positions including inside the vortex and followed the migration of the planet. We also examined the effect of various physical parameters such as: disc viscosity, surface density and planet mass. All models are summarised in Tab. 1.

We found that regardless of the planet position, disc viscosity or surface density, the planet migrates toward the vortex, interacts with it and eventually is locked to the vortex at a specific angular position far from the vortex center. In those models with the planet inside the vortex, the planet is expelled out of the vortex during the first hundreds orbits and afterwards the planet is locked to one side of the vortex.(Fig. 1). The planet's behaviour and locking position can be explained by the balance between different torque components on the planet: Lindblad torque and (very enhanced) corotation torque from the disc, star and vortex gravitational torques.

## Conclusion

Our study of the interaction between a low-mass planet and vortex inside a protoplanetary disc showed that, under the condition a large-scale vortex can be maintained, the planet is trapped and locked to the vortex efficiently. It can even happen for a planet as low mass as $5\times10^{-7}M_{\star}$. This has two consequences: the good one is that the vortex can serve as a "womb" and continue producing more planetary cores one after another, the dark side is that the planetary core is ejected by the vortex and could not grow to higher mass values.

## References

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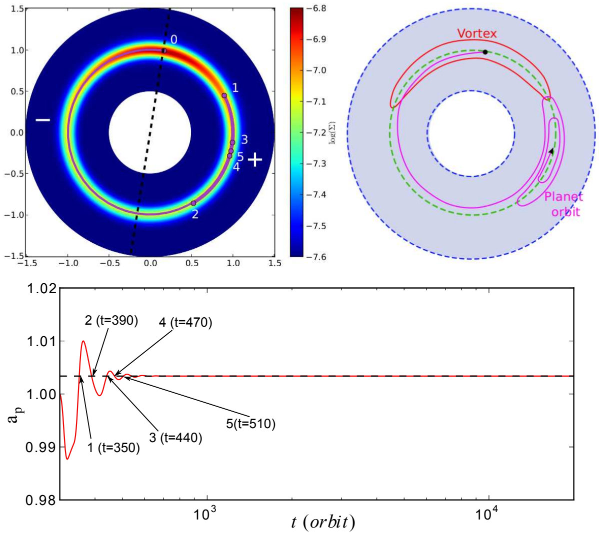


Figure 1: Planet trapping in the frame co-rotating with the vortex. The left upper panel demonstrates a planet initially set inside the vortex (position 0), comes out and moves to the position 1 and then return back to 2. Afterwards, it oscillates around position 5 until it is locked to the vortex at this location. We illustrate the planet's behaviour in the right upper panel in a more exaggerated way to show the radial migration of the planet as well. The lower panel shows the semi-major axis of the planet by time. The numbers denote the times of the marked positions in the left upper panel. We marked the positive and negative torques from the vortex by the $+$ and $-$ signs. The indirect torque from the star has the opposite sign of the vortex torque.


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