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INVESTIGATING THE ASYMMETRY IN THE DUST EMISSION IN THE INNER PARTS OF PROTOPLANETARY DISKS : A DUST-TRAPPING VORTEX ?

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Abstract. Interferometric observations conducted with the VLTI have revealed asymmetric near-infrared dust emission in the innermost regions of several protoplanetary disks. Moreover, some of these observations show a temporal variability in the asymmetry, which cannot be explained by axisymmetric disk models. We explore the hypothesis that a vortex generated by the Rossby Wave Instability (RWI) is responsible for dust trapping and, therefore, for the asymmetric emission. To investigate this scenario, we carried out 2D and 3D hydrodynamical simulations with the FARGO3D code to model the inner parts of protoplanetary disks, which feature a transition between an inner strongly turbulent region and an outer weakly turbulent region. Our simulations show that this transition can trigger the formation of a dust-trapping vortex due to the RWI, whose lifetime can be strongly increased by the presence of multiple planets near the transition region. Our simulation results are post-processed with RADMC-3D dust radiative transfer calculations to compute synthetic dust emission maps in the near-infrared, and synthetic interferometric observations are then produced with the ASPRO2 tool. In this proceeding, we discuss the possibility to reproduce, with our setup, the visibilities and closure phases provided by MATISSE observations of HD 163296.

Keywords: protoplanetary disks, hydrodynamical simulations, radiative transfer, interferometry.

1 Introduction

VLTI observations allow to probe the dust and gas emission in the innermost regions of protoplanetary disks (typically below 1 au). Interestingly, about one third of the disks around Herbig Ae/Be stars observed with PIONIER and GRAVITY display significant closure phases ($\gtrsim 20°$; GRAVITY Collaboration et al. 2019; Kluska et al. 2020). For some of them, temporal variability in the interferometric observables (visibilities, closure phases) has actually been reported (e.g., GRAVITY Collaboration et al. 2024). This suggests an asymmetric dust spatial distribution, whose origin remains to be explained. One example is the HD 163296 disk, which this work focuses on, and for which MATISSE L-band observations indicate an asymmetric dust emission at about 0.3 au from the star (Varga et al. 2021). One plausible scenario to explain a time-variable asymmetry in the dust emission is the presence of a dust-trapping vortex in the disc gas, which is generated by the Rossby-Wave Instability (RWI). In this work, we examine the feasibility of this scenario to explain the closure phases reported in the MATISSE observations of HD 163296 by Varga et al. (2021).

2 An example simulation

We performed 2D and 3D hydrodynamical simulations with the FARGO3D code to model the inner parts of the HD 163296 disk. The disk is expected to have a strongly turbulent cavity surrounded by a weakly turbulent denser region, and the 3D radiative MHD simulations of Flock et al. (2017) have shown that a vortex can form at the transition between both regions. To gain further insight, we have built up a simplified disk model where the aforementioned transition is modeled as a decreasing radial profile in the disk's turbulent viscosity, with a jump by a factor of 100 near 0.3 au. This jump entails the formation on an under-dense cavity with dust trapped at its outer edge. Our simulations show that if the viscosity jump is sharp enough, the sufficient criterion for

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the RWI formulated by Chang & Youdin (2024) is satisfied at the outer edge of the cavity, where an elongated vortex forms.

The dust trapped at the edge of the cavity behaves like a hot wall for the incoming stellar radiation, and radiative transfer calculations with RADMC-3D show that the disk temperature decreases quite sharply at this location (see also Flock et al. 2017). To mimic this effect, we have implemented a jump in the initial temperature profile in our hydrodynamical simulations, which is by a factor 2 near 0.3 au. Our FARGO3D simulations use an energy equation for which we have implemented a source term such that the disk temperature returns to its initial profile over a characteristic timescale that depends, among others, on Rosseland opacities.

An example simulation is shown in Fig. 1. As seen in the left panel, several vortices form at the edge of the cavity in the gas like in the dust (not shown here). A clear asymmetry is seen in the synthetic dust emission map displayed in the middle panel of the figure, which marks an enhanced dust emission at the location of the main vortex formed in the gas in our simulation. Further adding the star emission in the synthetic map enables to compute synthetic visibilities and closure phases with the ASPRO2 online tool. Synthetic closure phases are shown in the right panel of the figure for the same observing configuration as the L-band MATISSE observations in Varga et al. (2021). Our model reproduces the observed closure phases well.

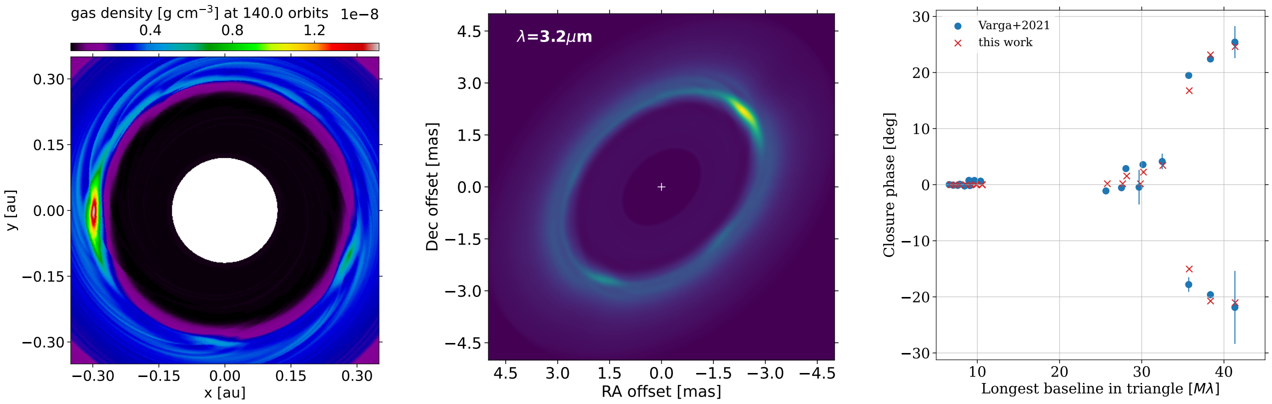

Fig. 1. Left: Gas midplane density after 140 orbits. The main vortex is the overdensity near 9 o'clock. **Middle:** Specific intensity of dust emission obtained with RADMC-3D at 3.2 μm for dust sizes set to $[0.1; 1; 10]$ μm and a total dust-to-gas mass ratio of 10^{-7}. **Right:** Closure phases computed by ASPRO2 (crosses) and compared with observations (Varga et al. 2021, circles). Synthetic closure phases use the dust emission map with added stellar emission, assuming a star-to-disk flux ratio of 11.5% in the L-band.

3 Future work

Our hydrodynamical simulations and dust radiative transfer calculations show that a dust-trapping vortex could explain the closure phases observed with VLTI/MATISSE in the HD 163296 disk. Our work shows that the asymmetry in the dust emission naturally arises from the structure and dynamics of the disc's inner parts. It provides a physical foundation for the non-axisymmetric ring model of emission that is commonly used to fit interferometric data. Still, in our simulations the vortex decays in a few hundred orbits at the vortex's location, which translates into a few tens of years only. Preliminary simulations that further include multiple planets show that the vortex's lifetime can be considerably increased, which we will show in a future publication.

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