Konkoly Observatory's
Computational Astrophysics Group

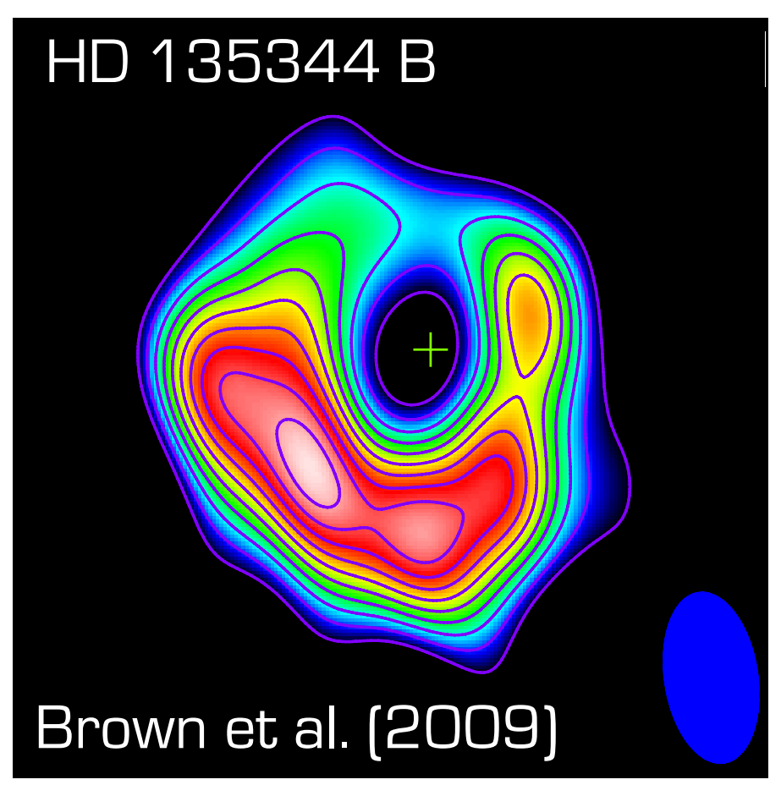
INTERPRETING BRIGHTNESS ASYMMETRIES IN TRANSITIONAL DISKS

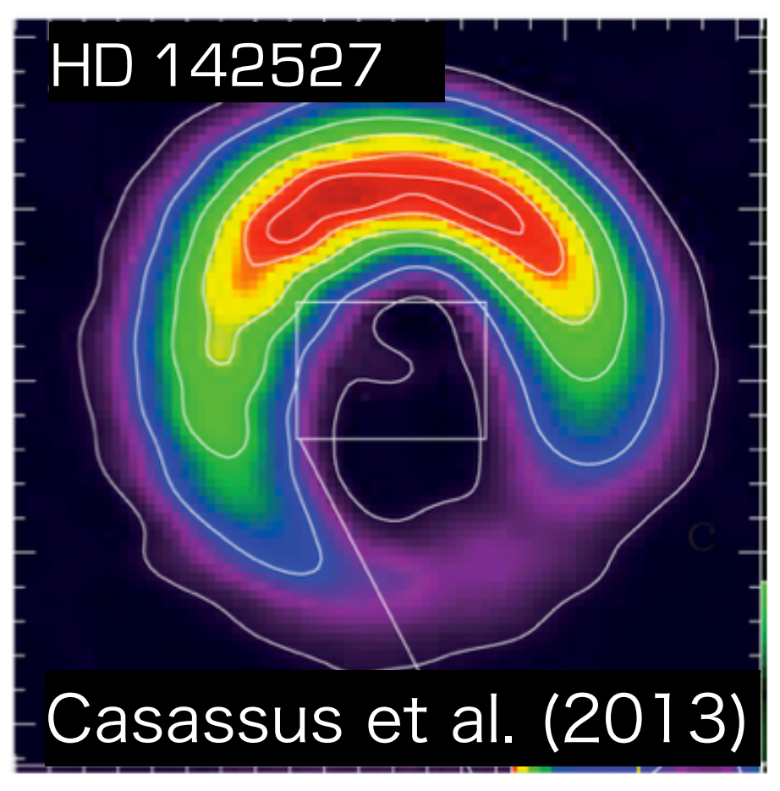
VORTEX AT DEAD ZONE OR PLANET CARVED GAP EDGES?

Zs. Regály[1], A. Juhász[2,3]

1 - Konkoly Observatory, Hungarian Academy of Sciences, P.O. Box 67, H-1525 Budapest, Hungary, e-mail: regaly@konkoly.hu
2 - Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
3 - Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

ABSTRACT





As of today, two competing scenarios exist to explain recent sub-millimeter observations of transitional disks with azimuthally extended non-axisymmetric brightness distribution. Both scenarios assume non-axisymmetric dust accumulation in a large-scale vortex, which results in the formation of azimuthal brightness asymmetry. We investigated both scenarios in order to test their viability. We found that the vortex formed at the gap outer edge is short-lived, unless the disk is inviscid, while it is long-lived in dead zone bearing disks. The density asymmetry is found to be spatially more extended in dead zone than in gap models. We showed that the formation process of vortices can be inferred by analyzing the brightness morphology in high-resolution ALMA images.

INTRODUCTION

One of the striking discoveries of recent sub-millimeter observations are the continuum images of transitional disks revealing azimuthally extended non-axisymmetric brightness distribution for several cases; e.g., HD-135344B and SR-21 (Brown et al. 2009, Pérez et al. 2014); LkHα-330 (Brown et al. 2009); HD-142527 (Fukagawa et al. 2013, Casassus et al. 2013); Oph IRS-48 (van der Marel et al. 2013). Since these disks are optically thin in the sub-millimeter continuum, the brightness asymmetry reflects any asymmetries in the surface density of dust.

The accepted explanation for the observed asymmetries is the accumulation of dust grains in pressure maxima, in the core of vortices. These dust traps can be the very places where planets and planetary cores can be quickly assembled in the core-accretion scenario.

Such vortices can be developed by the excitation of Rossby wave instability (RWI) in the vicinity of steep pressure gradients formed at the edges of a giant planet carved gap or edges of disk's dead zone (Fig 1.). We investigated whether or not we can infer the formation mechanism (gap vs. dead zone) of the vortex from the morphology of the disk as seen in sub-millimeter ALMA observations.

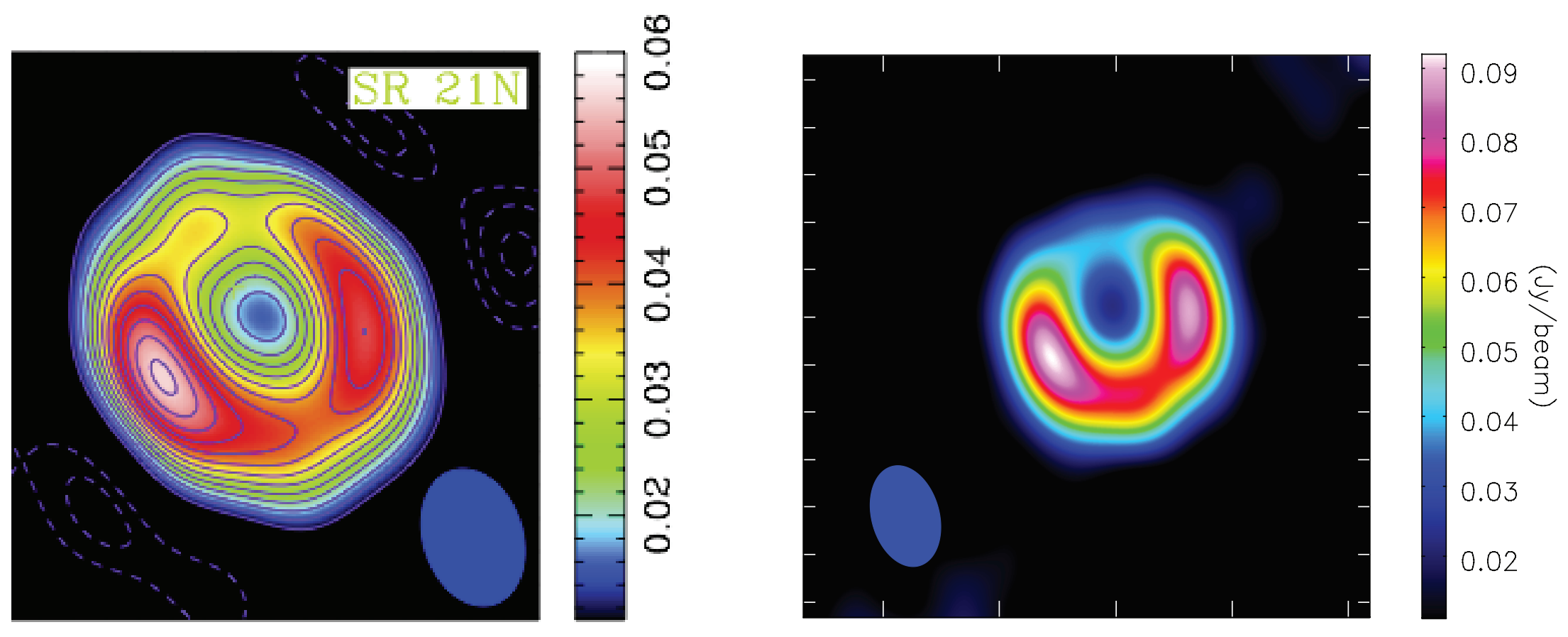


FIGURE 1. – SR21 observed with SMA (Brown et al. 2009) on the left and synthetic image of a disk modeled with a vortex formed at the outer edge of a dead zone (Regály et al. 2012) on the right.

VORTEX DEVELOPMENT

We studied both vortex formation mechanisms by means of 2D locally isothermal hydrodynamical simulations of disks with α-type viscosity using the GPU-based FARGO code (Masset 2000). We modeled 1) the vortex formation at the edges of a giant planet (R_p=10AU, $M_p/M_\star=5\times10^{-3}$) carved gap (Fig. 2, left panel) in three different viscosity regimes ($\alpha=10^{-3}$, 10^{-4}, 10^{-5}), and 2) the vortex formation in a disk that has a sharp dead zone edge (Fig. 2, right panel). In the dead zone model the value of α was smoothly reduced to 1% of its original value at distance of R_{dze}=12AU within $\Delta R_{dze}=1H_{dze}$ and $1.5H_{dze}$ dead zone edge width.

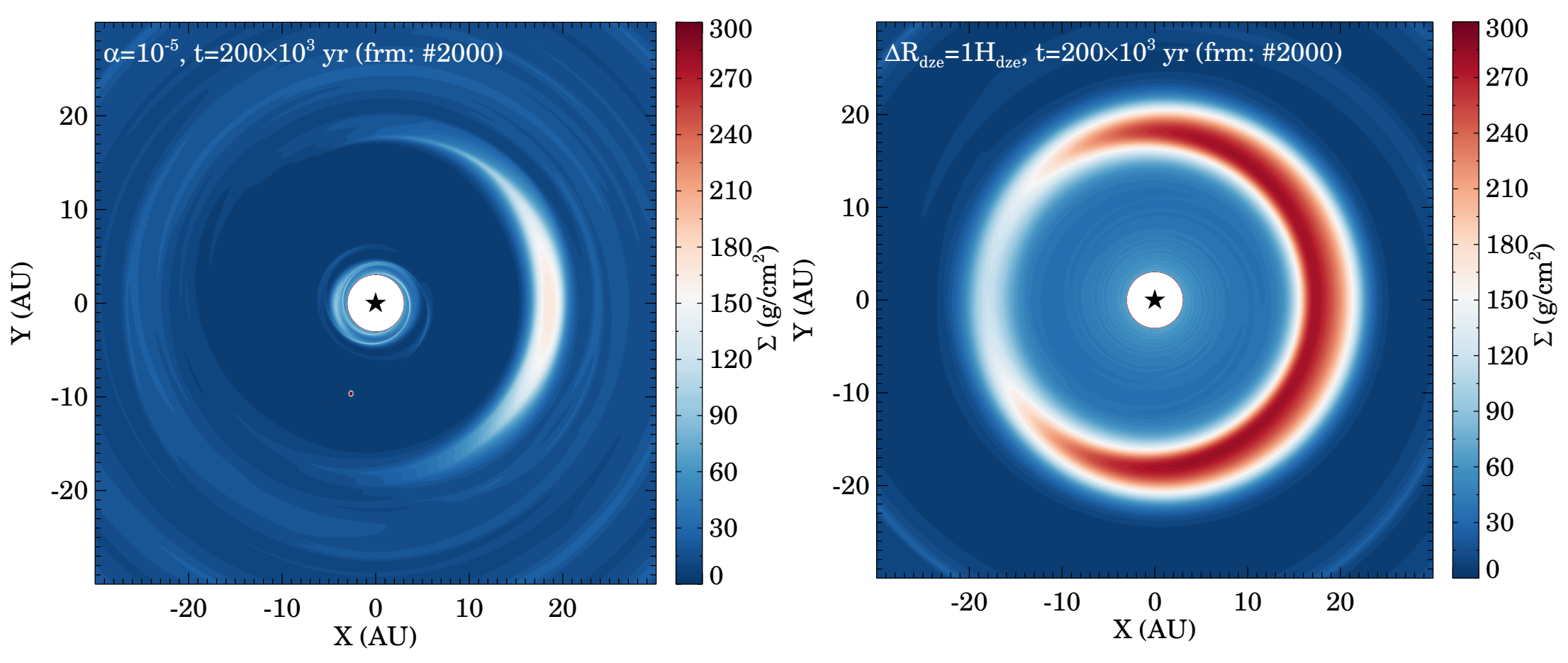


FIGURE 2. – Surface density distributions in the GAP model (left) and DZE model (right). The vortex is spatially more extended, while the azimuthal contrast in gas density is significantly lower in DZE than in inviscid GAP models.

VORTEX LIFE-TIME: The vortex vanishes by ~300, 3000 orbits of the planet for $\alpha=10^{-3}$, 10^{-4}, respectively. This transient nature of the vortex is in agreement with Ataiee et al. (2013), and Fu et al. (2014). The vortex survives up to the end of the simulations (6350 orbits) for $\alpha=10^{-5}$ GAP and in DZE models. The gradient in the azimuthally averaged radial density profile (Fig 3.) is too shallow in viscous ($\alpha>10^{-5}$) GAP models, while steep enough in nearly inviscid ($\alpha\leq10^{-5}$) GAP model and in DZE models to excite RWI.

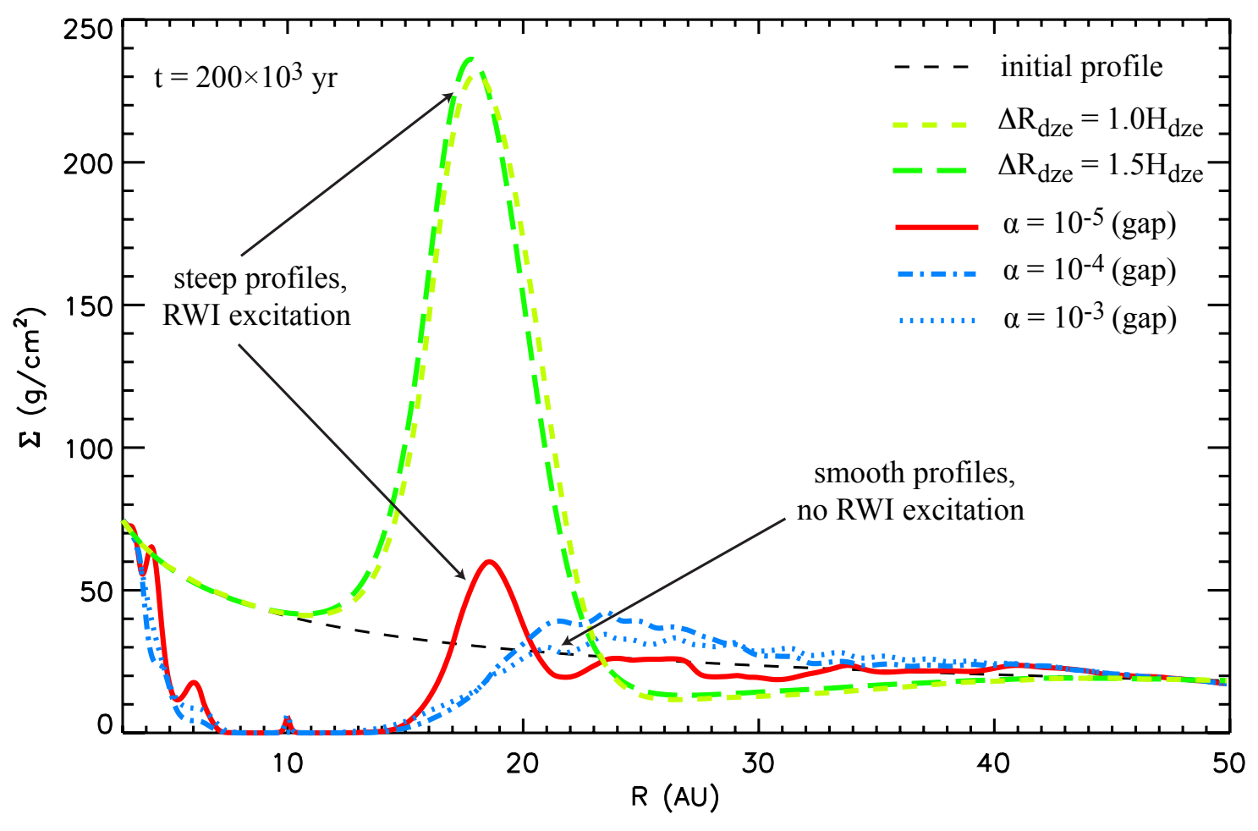


FIGURE 3. – Azimuthally averaged density profiles in GAP and DZE models.

VORTEX MORPHOLOGY: The azimuthal contrast in the density profile averaged over the extent of the vortex (Fig 4.) is high (~12) in the inviscid GAP models, while low (1.5–3) in DZE models. The density enhancement is azimuthally as well as radially wider in DZE than in GAP models (Figs 3. and 4.).

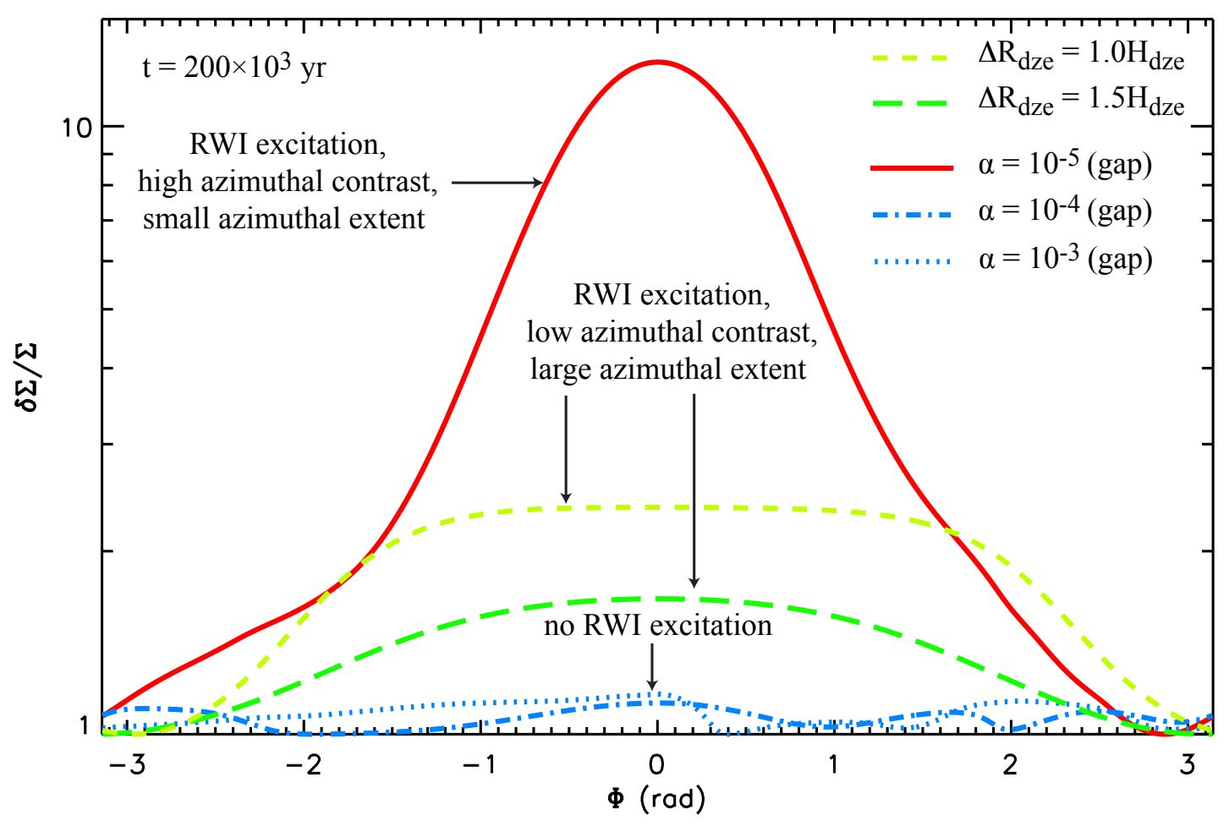


FIGURE 4. – Radially averaged density profiles in the GAP and DZE models. The radial averaging was done over the extent of the vortex.

OBSERVABILITY WITH ALMA

To create synthetic images first the output of the FARGO simulations were fed into the 3D radiative transfer code RADMC-3D (Dullemond et al., in prep) to calculate the dust temperature structure. We assumed a constant gas-to-dust ratio of 100 and a power-law grain size distribution between 0.1μm and 1000μm with a power exponent of -3.5. Then images were calculated at 880μm at inclination angles of 30 and 60 deg. ALMA observations were simulated using the Common Astronomy Software Applications v4.2. The simulated observations contained thermal noise with a precipitable water vapor column of 1.3 mm. We used three different antenna configurations for the full baseline array resulting in spatial resolutions of 0.1", 0.05" and 0.025", respectively. We used the full 7.5GHz bandwidth and the duration of the observations was set to 4 hours.

EFFECT OF SPATIAL RESOLUTION: Brightness asymmetries, caused by the vortex are clearly visible in the images at all simulated spatial resolutions for both the GAP and DZE models (Fig 4.). The azimuthal contrast in ALMA images is severely reduced at low spatial resolutions (0.1", 0.05") in the GAP models, due to beam dilution, compared to the contrast derived from the hydrodynamical frames. However, in DZE models the azimuthal contrast is insensitive to spatial resolution in the tested range. The inner edge of the gap appears to be eccentric in the GAP models, due to beam convolution effects at low spatial resolutions.

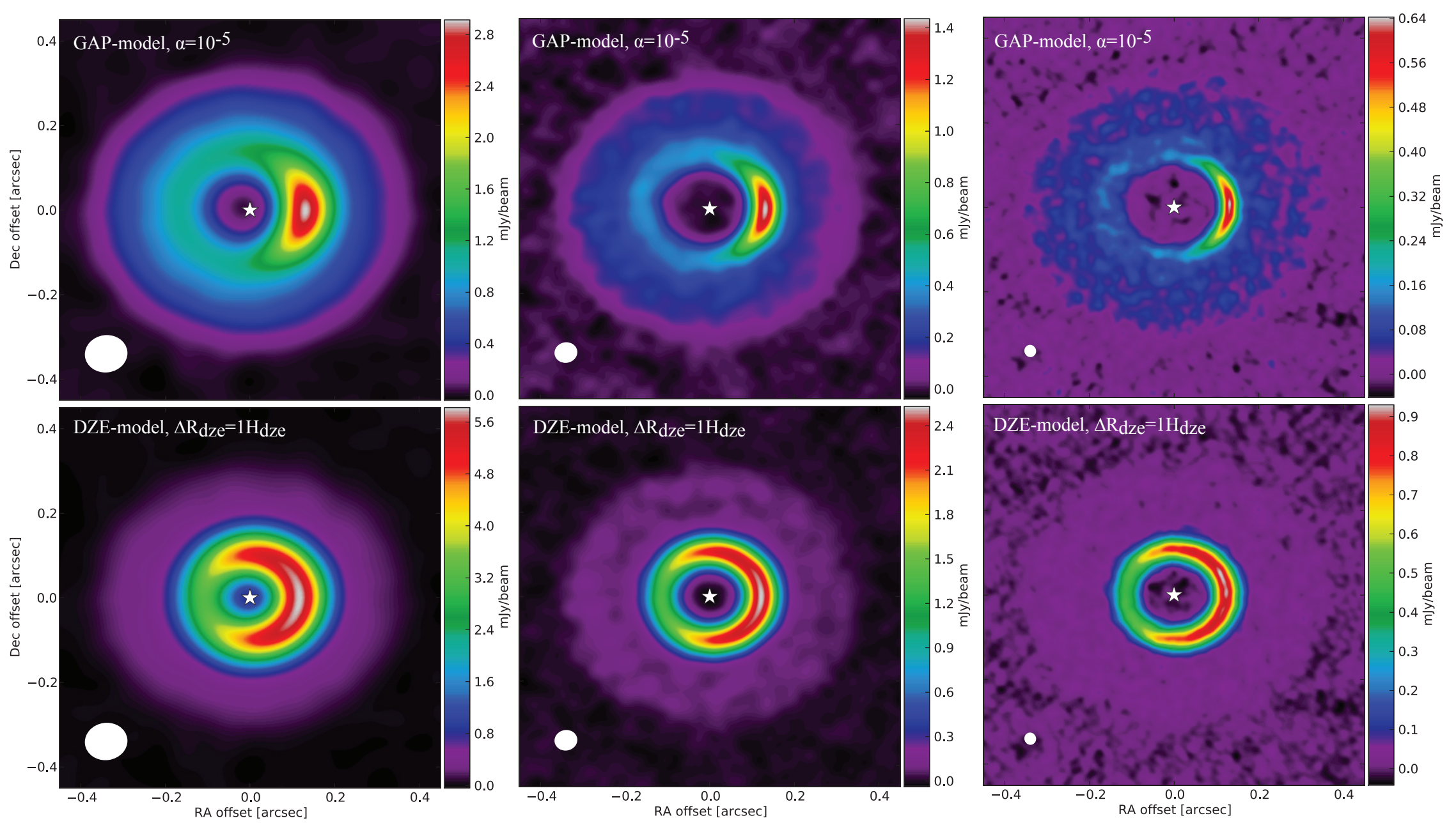


FIGURE 4. – Synthetic ALMA images in GAP (upper) and DZE (lower) models with spatial resolutions of 0.1", 0.05" and 0.025".

EFFECT OF VORTEX POSITION: Due to the low azimuthal contrast in DZE models, the vortex splits into two separated blobs in low-resolution images, if the disk is seen in high inclination angle, e.g. 60 deg, (Fig 5.). In contrast, the vortex is well defined in GAP model due to the high azimuthal contrast.

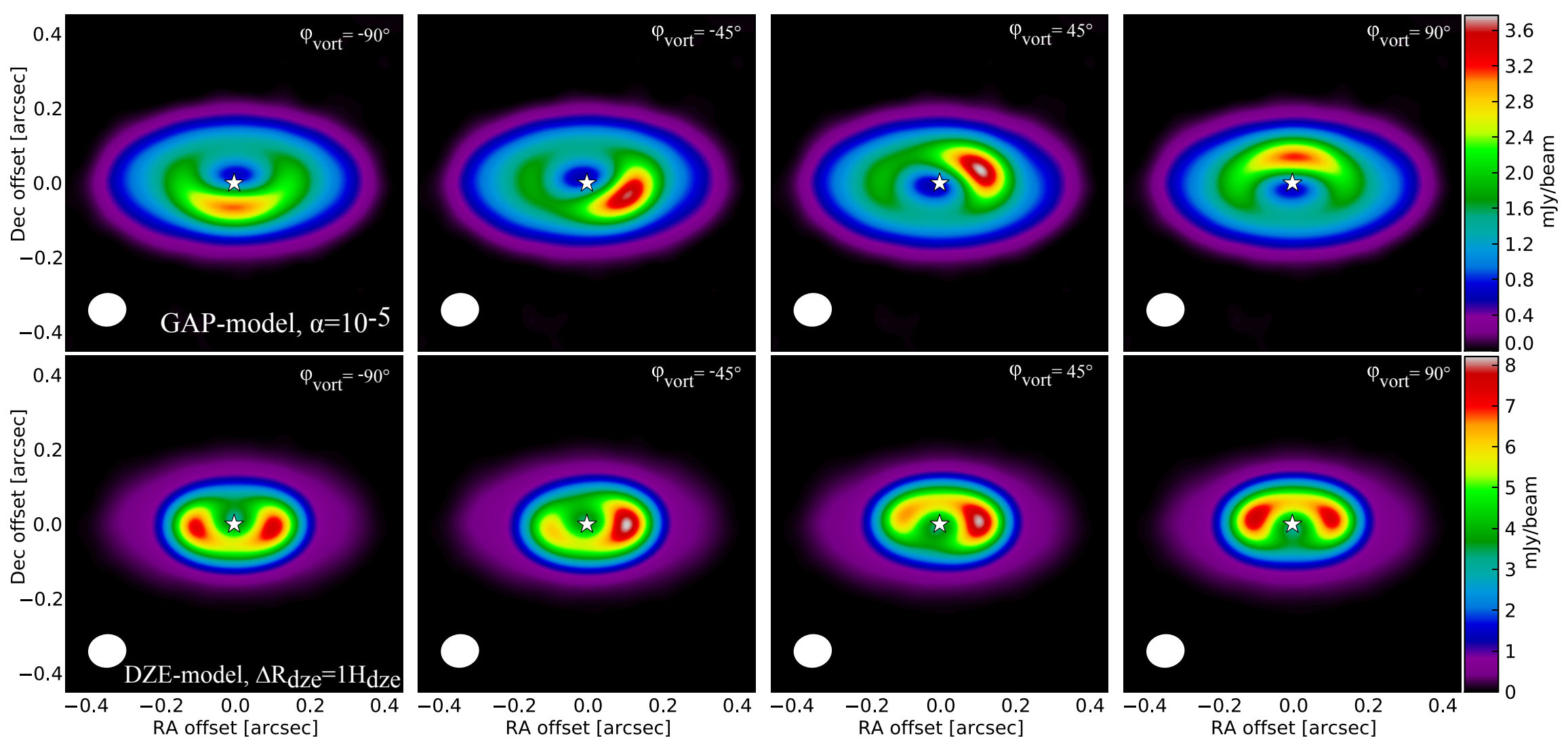


FIGURE 5. – Effect of the vortex position on the synthetic ALMA images at low-inclination angle and low spatial resolution (0.1").

CONCLUSION

Vortices excited at the gap edge carved by a giant planet have a different morphology compared to that of vortices excited at the dead zone outer edge. Vortices at gap edges are azimuthally more compact and have higher azimuthal contrast than their counterparts at the edge of a dead zone.

It is thus possible to infer the excitation mechanism of such vortices by studying the shape and the contrast of surface-brightness asymmetries in sub-millimeter, especially in ALMA observations. One needs, however, a spatial resolution that is similar to or higher than the radial extent of the vortex to measure the true contrast between the vortex and the background disk. At lower spatial resolution the observed contrast can be severely lowered by beam-dilution.

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