Effect of Dust Coagulation on the Sub-structures in Protoplanetary Disks

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1. Introduction

Vortices/rings in protoplanetary disks (PPDs) may play essential roles in the early stage of planet formation due to their effectiveness in trapping dust, which could be an ideal place to trigger planetesimal formation. In this work, we explore the consequences of dust coagulation on the dust dynamics and vortices/rings morphology.

2. Method

We run 2D hydrodynamic simulations by the LA-COMPASS (Li et al. 2005, 2009, Fu et al. 2014) to study the effect of coagulation on the vortex/ring evolution induced by a planet embedded in a low viscosity protoplanetary disk.

For the vortex case, the planet mass is fixed at 5 M_J and located at r_0, and the viscosity parameter $\alpha = 7\times10^{-5}$ (van der Marel et al. 2013, Fu et al. 2014). We run four models to quantify the effect of coagulation on the vortex evolution. One includes 2D coagulation (Li et al. 2019; Drążkowska et al. 2019) and the other two are for a single dust species with the dust size fixed at $a = 4.0$ mm or $a = 0.2$ mm. The size $a = 4.0$ mm is close to the Σd-weighted dust size during the evolution of our coagulation model, while $a = 0.2$ mm is the commonly used dust size for the single-species run. To mimic the coagulation run, we also have another run with five species of dust logarithmically uniform spaced between 1.0 μm and 4.0 mm with an initial MRN distribution to examine the long-term evolution behavior. Our simulation domain extends from $0.4r_0$ to $16r_0$ with a grid of resolution $n_r \times n_\phi = 4096 \times 3456$.

For the multiple rings case, The planet masses vary between 10 $M_\oplus$ and 50 $M_\oplus$ and disk scale height H_0 at r_0 varies between 0.03 and 0.07. The grid of resolution is $n_r \times n_\phi = 1024 \times 1024$ extending radially from $0.4r_0$ to $16r_0$.

3. Results

3.1. Vortex case: Dust/gas dynamics

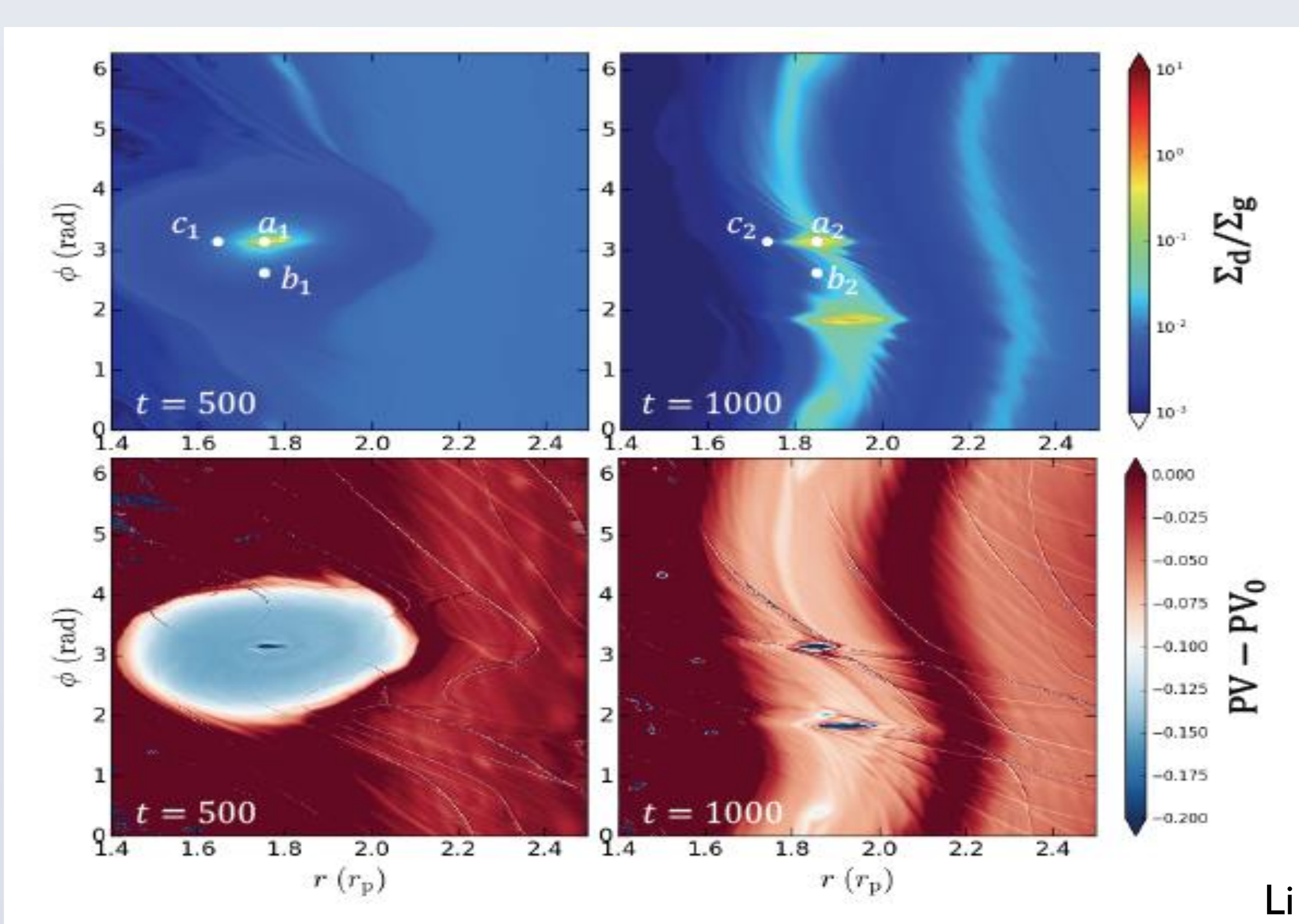

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Figure 1: Gas and dust dynamics around the gaseous vortex region for the coagulation run. Upper panels: total Σd/Σg for all dust species at 500 (left) and 1000 (right) orbits. Lower panels: potential vorticity (PV) subtracted from the initial value at 500 (left) and 1000 (right) orbits.

Strong dust feedback when $\Sigma_d/\Sigma_g \sim 1$

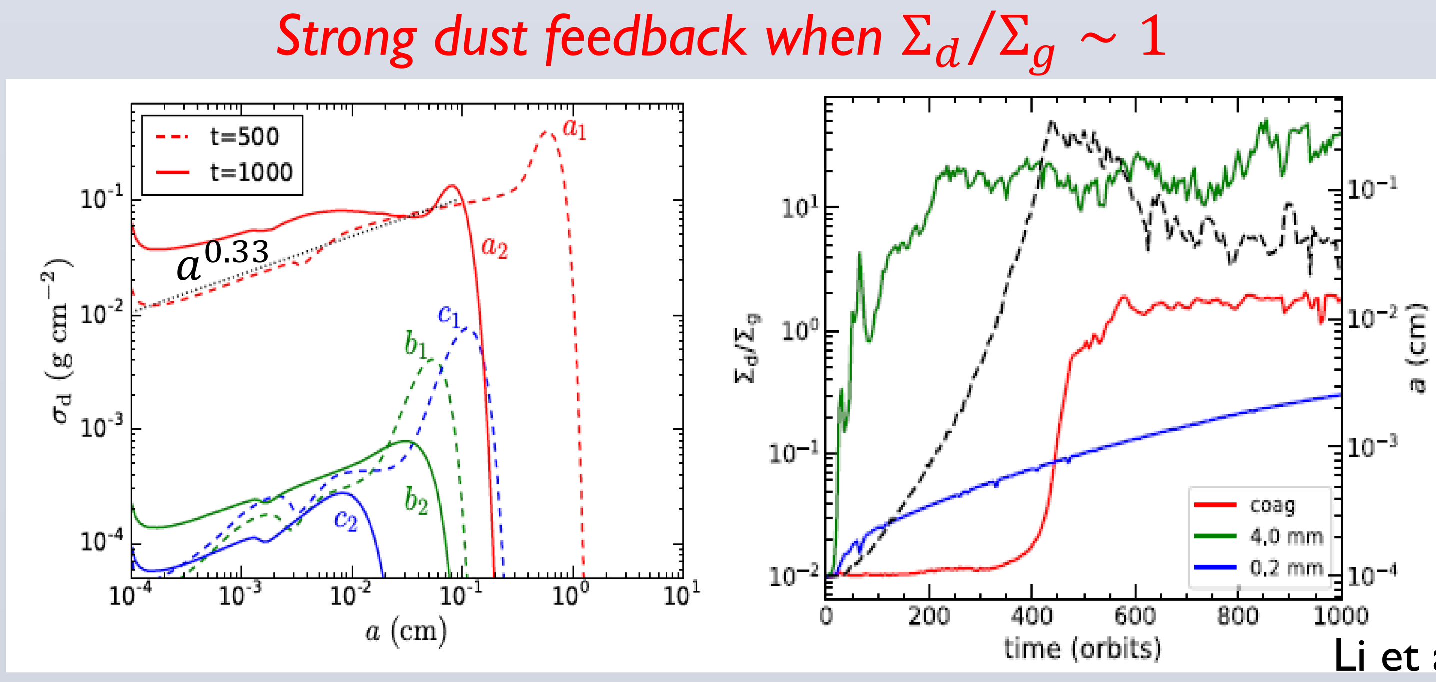

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Figure 2: Left panel: dust size distribution at three locations, which are marked in the upper panels of Figure 1. Right panel: the time evolution of the dust-to-gas ratio Σd/Σg at the vortex center (i.e., the location of maximum Σd) for three models (color solid lines). The black dashed line shows the Σd-weighted dust size *a* evolution at the vortex center for the coagulation model.

- Dust size is quite non-uniform within vortex region
- Dust size growth facilitates the increase of dust/gas ratio.
- Vortex (lifetime) can be significantly impacted by dust feedback with coagulation.

3.2. Vortex case: Synthetic Dust Emission

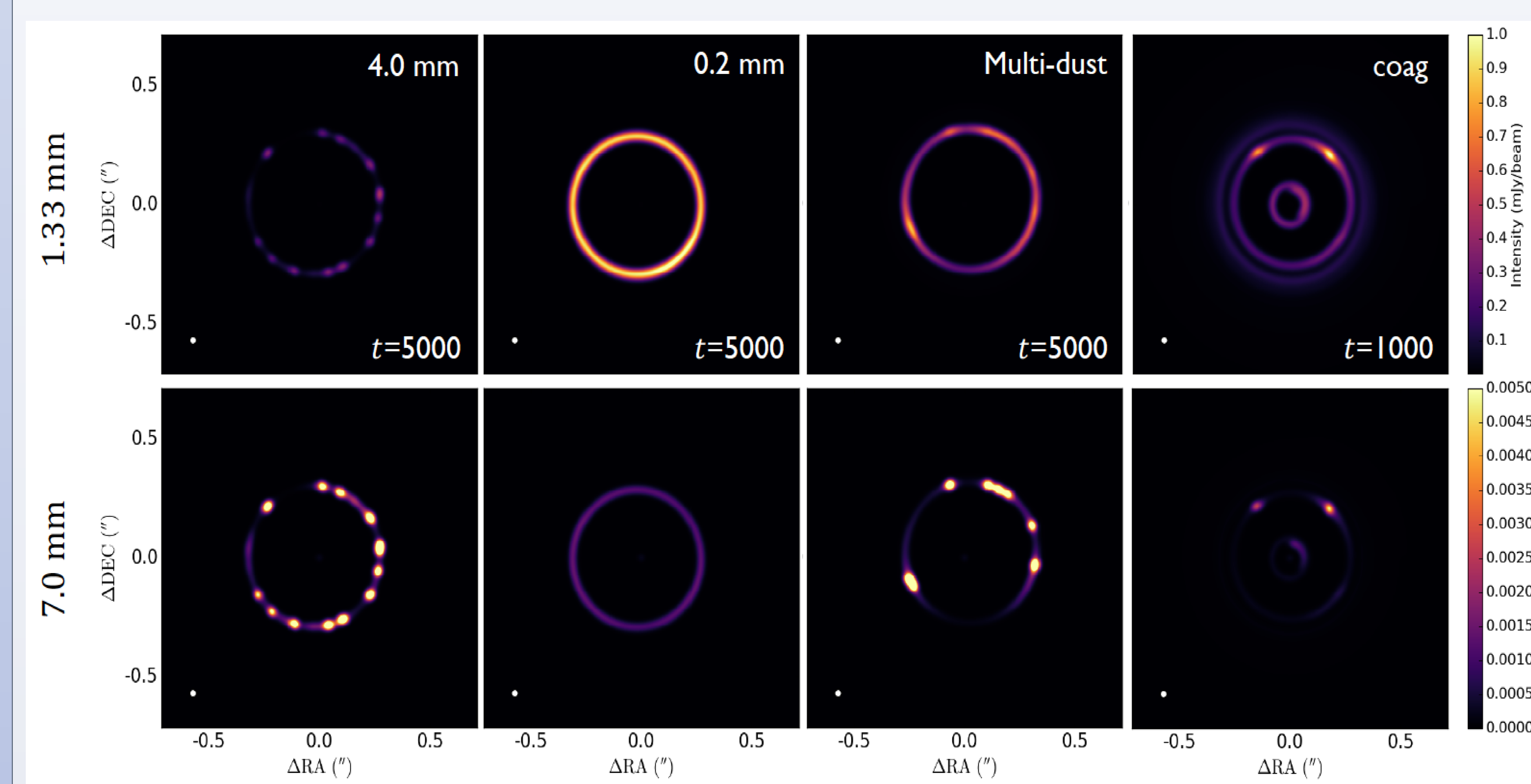

Figure 3: Clumpy at longer wavelength, while rings at (sub)mm band for coagulation models.

3.3. Effect of Coagulation on Multiple Rings

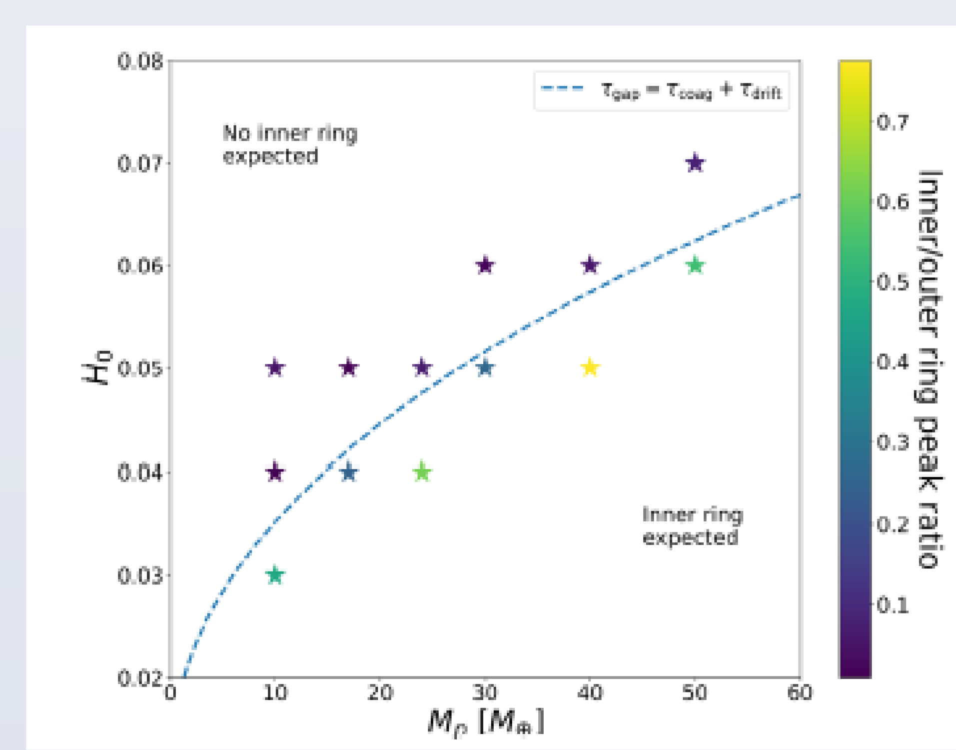

Figure 4: Ratio between the outer ring's peak density and the inner ring's peak density for all full-coagulation runs. The dashed line is where the timescales $\tau_{gap} \simeq \tau_{coag} + \tau_{\rm drift}$.

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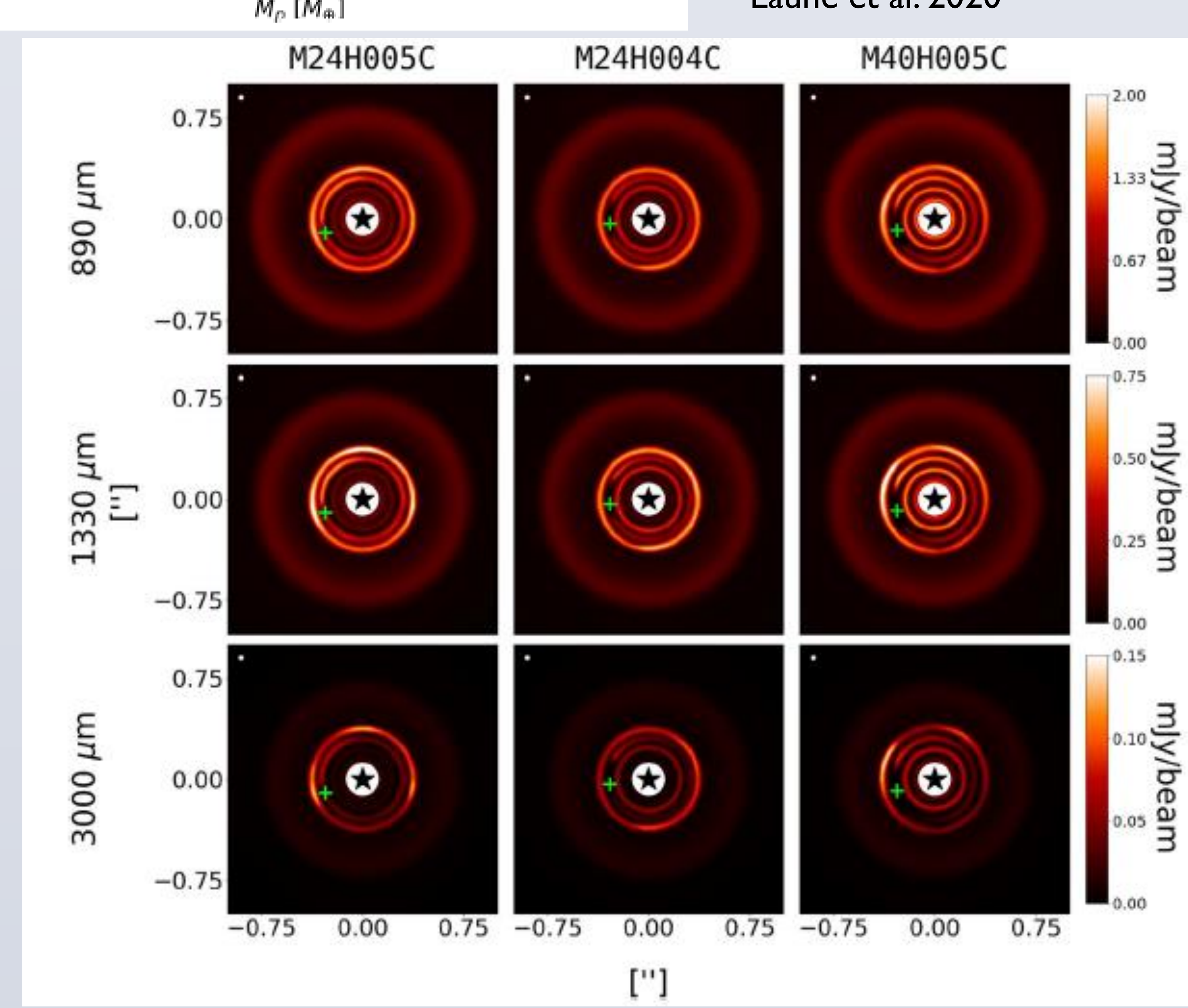

Figure 5: If the planet doesn't open a gap quickly enough (low planet mass or large scale height), an inner ring is impeded due to dust coagulation and subsequent radial drift.

4. Conclusions

- Dust substructures in PPDs can effectively trap dust, facilitates dust size growth.
- Coagulation affects significantly ring/horseshoe morphologies in PPDs.
- Vortex evolution lifetime can be significantly affected by dust coagulation.

5. References

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