Origins: From the Protosun to the First Steps of Life
Proceedings IAU Symposium No. 345, 2018
B. G. Elmegreen, L. Viktor Tóth & M. Güdel, eds.
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doi:10.1017/S1743921319001923

3D radiation MHD simulations of gas and dust in protoplanetary disks

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Abstract. 3D global radiation MHD simulations of gas and dust in protoplanetary disks allow us to understand the dynamical and thermal evolution of protoplanetary disks. At the same time, recent observations in the mm-dust emission by the Atacama Large Millimeter Array (ALMA) allow us to resolve structures at scales of the disk scale height.

From our recent simulation results by Flock *et al.* (2015) and Flock *et al.* (2017) we are able to directly compare for the first time detailed observational constraints from high-resolution observations by ALMA with the gas and dust dynamics obtain in 3D state-of-art simulations of protoplanetary disks. Especially measurements of the dust scale height obtained from the disk around the young system HL Tau allow us to compare for different gas disk instability models. Further we use Monte Carlo radiation transfer models of the dusty disk to compare our results of the dust scale height in 3D radiation HD and MHD simulations. Our findings are that magnetized models fit perfectly the observational constraints, showing a strongly settled disk, while hydrodynamical turbulence leads to a dust uplifting which is larger than expected. These results open a new window to compare future multi-wavelength observations to simulations.

Keywords. MHD simulations, accretion disks, protoplanetary disks, mm observations

1. Introduction

Planet formation is one of the key research topics in modern astrophysics. Especially the discovery of thousand new exoplanetary systems (Dressing & Charbonneau 2015) have raised the question about their formation. For this we have to look into young circumstellar disks, often called protoplanetary disks which are typically less then 10 million years old. The advancement in telescopes and observations allow us now to get a direct constrain on the physical structure of the disk. Dust grains around micron size and smaller are coupled to the gas structure and motion in protoplanetary disks. Observations of the near infrared traces the scattered light from tiny dust grains in the disk atmosphere and they allow us to learn about the gas structure as well. Recently this was done for the disk system around IM Lup by Avenhaus *et al.* (2018) showing the flared disk structure or for the disk around HD 169142 by Bertrang *et al.* (2018) showing a more complex ring and gap structure. Larger grains of millimeter and centimeter sizes start to decouple from the gas motion. They start to settle to the disk midplane and they drift to disk regions which have a local pressure maximum (Weidenschilling 1977). The structure of these large grains were observed in the disk around HL Tau (ALMA Partnership *et al.* 2015) with a so far surpassing resolution. These observations alow to determine the dust scale height in the disk. Pinte *et al.* (2016) concluded from best fit radiation transfer models that a dust scale height of $H_{dust}/R = 0.007$ fits best the scale height of mm sized grains. In the following we will investigate the dust scale height from hydrodynamical and magnetohydrodynamical models.

https://doi.org/10.1017/S1743921319001923 Published online by Cambridge University Press

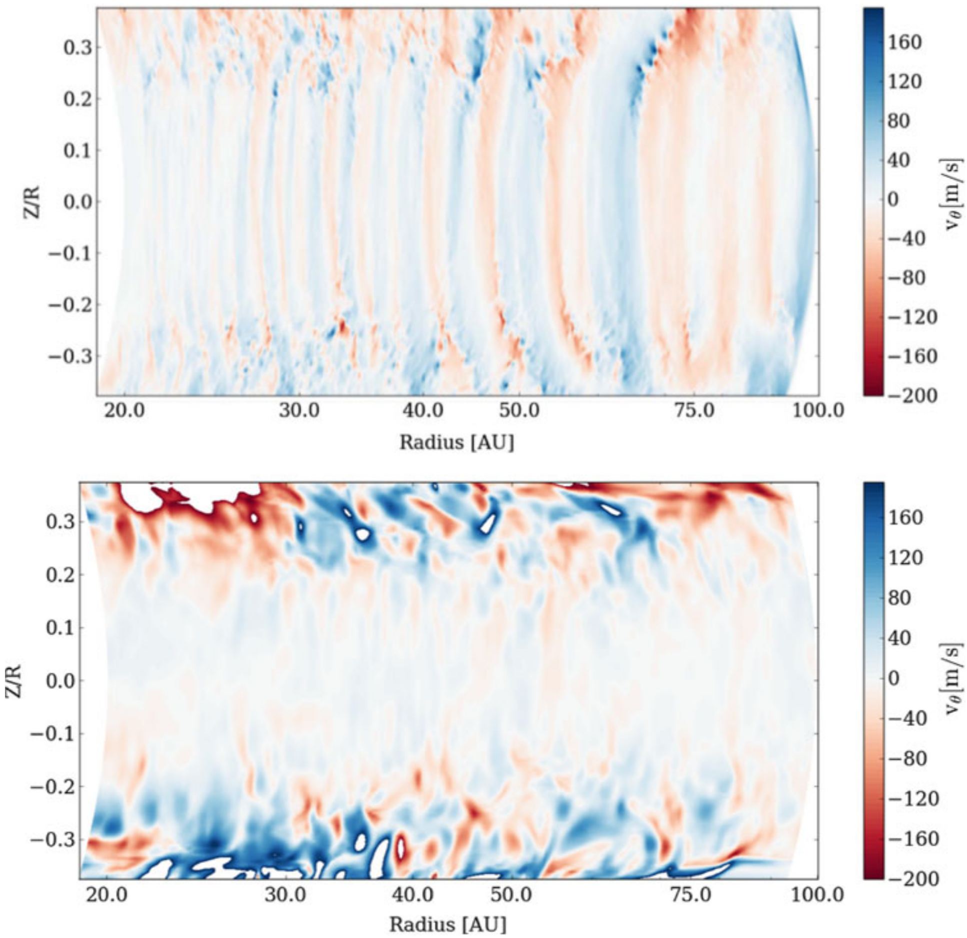

Figure 1. Top: Snapshot of the vertical velocity component for the 3D radiation hydrodynamical model Flock *et al.* (2017). Bottom: Snapshot of the vertical velocity component for the magnetized disk model by Flock *et al.* (2015). Both are in the R - Z/R plane for a given azimuthal slice.

2. Models and results

The 3D models are based on 3D radiation HD and MHD simulations with embedded grains of different sizes. Both models assume the same stellar and disk parameter for the initial conditions. For details on the models we refer to Flock *et al.* (2017), Ruge *et al.* (2016) and Flock *et al.* (2015). Fig. 1 presents a snapshot of the vertical velocity in the R - Z/R plane for a given azimuthal slice. The hydro model, Fig. 1, top, shows characteristic vertical motions of the disk bulk material of around 50 m/s at the disk midplane. Those motions easily overshoot the midplane region which emphasizes the need of fully stratified models of both hemispheres. In contrast, the corresponding magnetized model by Flock *et al.* (2015), Fig. 1 bottom, shows turbulent motions with smaller amplitude at the midplane compared to the hydro model.

Fig. 2 summarizes the results of two grain sizes which are embedded in the simulation by including individual particle motion with a drag term. The hydro model, Fig. 2 left, shows 100 μm grains well mixed. The 1 mm grains are mixed less efficiently. Their profile shows a quasi-plateau with a dropoff above one gas scale height. This extent of the plateau

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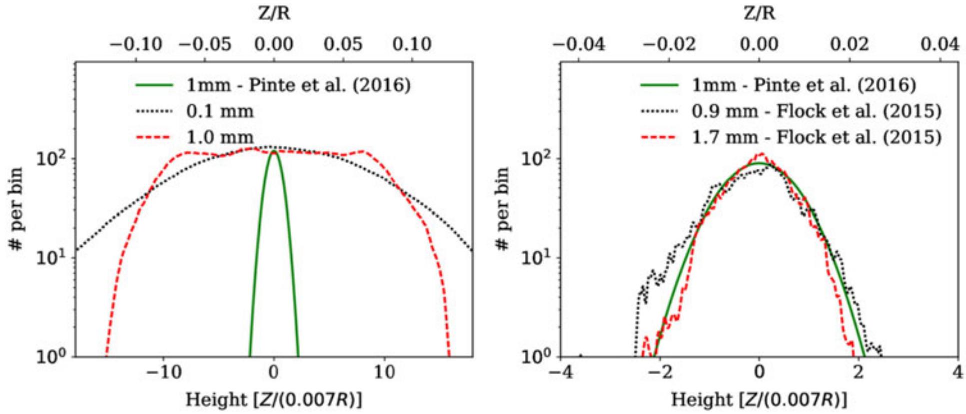

Figure 2. Time- and space-averaged vertical distribution of two grain sizes. Left: grain data set for the hydro model. Right: grain distribution for the magnetized disk model. For both plots, the green line shows the best-fit value of $H/R = 0.007$ which was found for the systems HL Tau by Pinte *et al.* (2016).

matches the extent of the vertical bulk motions created by the vertical shear instability (VSI), which appear within one scale height above and below the disk midplane. These large-scale vertical oscillations move the bulk of the 1 mm grains up and down. Clearly the dust scale height of those grains is much larger than the value found for HL Tau. For the MHD models, Fig. 2 right, we show 0.9 and 1.7 mm grain sizes which were trapped between 40 and 50 au in a pressure bump. The particle vertical distribution of those magnetized models fits very well with the best-fit model by Pinte *et al.* (2016) for HL Tau.

3. Conclusion

New spatial resolved observations of the dust continuum of protoplanetary disks in the mm emission enable for the first time to give constraints on the dust scale height. Such measurements are a promising way to learn also about the underlying disk physics, e.g. the strength of gas turbulence and mixing. By comparing 3D radiation non-ideal HD and MHD simulations with gas and dust we found that magnetized disk models fit best the observational constraints for the young protoplanetary disk HL Tau. Future simulations and observations should target the determination of the dust scale height. Especially highly-inclined disks should be suited to determine the dust scale height by using the thermal emission for different wavelengths. At the same time future simulations of gas and dust are needed to learn more about their interaction and to finally understand the relevant physical processes in these young disks.

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Discussion

KHAIBRAKHMANOV: What value of plasma β did you observe in your simulations? Can the radial pressure of the magnetic field influence the position of pressure bumps in the disk?

FLOCK: The initial plasma β is 10^4 at the midplane. It is a vertical magnetic field. During the simulation the plasma β changes locally, being high in the pressure bump and low inside the gap.

KAMP: Can you explain if there are any limitations arising from the fact that you consider trace dust of single size, so neglecting dust colliding with itself (maybe leading to growth or destruction)?

FLOCK: The dust growth becomes important on timescales of roughly 100 orbits. For the simulation I presented, this is mostly not important. However, locally, the dust could concentrate which would decrease the timescale.

KAMP: Do your 1μm particles agree with SPHERE data spatial distribution?

FLOCK: We are going to investigate this soon.

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