Astronomy & Astrophysics manuscript no.
(will be inserted by hand later)

Global dust drift in evolving disks with planets

C.P. Dullemond[1], T. Birnstiel[2], Z. Zhu[6], S. Zhang[6] , N. Troncoso[3], L. Perez[3], S. Andrews[4], A. Isella[5], J. Huang[4], V. Guzmán[7], M. Benisty[8], J. Carpenter[9]

(1) Zentrum für Astronomie, Heidelberg University, Albert Ueberle Str. 2, 69120 Heidelberg, Germany
(2) **XXXX** (3) **XXXX** (4) **XXXX** (5) **XXXX** (6) **XXXX**

July 2, 2018

Abstract. Ever since multi-ring structures were seen in HL Tau and TW Hydra, it has been speculated that these rings are, in fact, the gaps caused by embedded planets in these protoplanetary disks. The ALMA Large Programme P484 shows that many, if not most, protplanetary disks display such multi-ringed structure. In this paper we investigate the drift and trapping of dust in a disk with embedded planets. We focus on the long-term radial evolution, where we approximate the disk as being axially symmetric. The gaps produced by the planets are implemented using a parameterized gap model by Zhang et al. ([**REF**]). **CONCLUSIONS**

Key words. accretion, accretion disks – circumstellar matter – stars: formation, pre-main-sequence – infrared: stars

1. Introduction

ALMA observations of protoplanetary disks often show that the dust in these disks is arranged in multiple concentric rings (ALMA Partnership et al. 2015; Andrews et al. 2016; Isella et al. 2016; Fedele et al. 2017; Cieza et al. 2017; Huang et al. 2018; Dipierro et al. 2018). It is tempting to interpret these structures as the result of planet-disk interaction, where an embedded planet opens a gap in the protoplanetary disk. [**Maybe a list of papers proposing this here?**] It is known for a long time that even relatively low mass planets that open only very weak gaps in the gas, may open strong gaps in the dust (Paardekooper & Mellema 2004), if the dust particles are large enough. Such a process may lead to dust filtration, where small grains flow through the gap with the gas, while large grains get trapped in the pressure bump in the outer gap edge (Rice et al. 2006). The fact that larger dust aggregates ("pebbles") do not make it through the gap, also tends to choke off the delivery of solids to growing planetary cores when these cores reach their "pebble isolation mass" (Lambrechts et al. 2014; Bitsch et al. 2015). This is then thought to lead to runaway gas accretion and the formation of a gas giant planet.

In our ALMA Large Programme P484 [**REF PAPERs**] we made continuum images of 20 disk sources at the largest angular resolution in band 6 ($\lambda = 1.3\,\mathrm{mm}$). We find that a large fraction of these sources have concentric rings in dust continuum. Apparently these structures are very common, and the interpretation in terms of embedded planets particularly appealing.

Could it be that the multiple concentric dust ring structures we are seeing are indeed the result of embedded planets? This question is not easy to answer, since the true "smoking gun", a planet directly observed as a point source within the gap, is not seen in any of these disks yet. In one of our sources, HD 163296, **Pinte et al.** found indications of the presence of a planet at a semi-major axis beyond the dust rings in our observations. Another paper reports axially symmetric deviations from Keplerian velocity within the dust gaps, which might be caused by planets, but are also consistent with any process leading to a series of concentric pressure bumps. Even more recently **Keppler et al.** report the presence of a directly imaged planet inside of the hole of a transitional disk **PDS 70**. While exciting and promising, none of these reports directly indicate a planet being *inside* of the narrow rings of multi-ringed non-transitional disks.

In a companion paper [**Zhu et al. REF**] we study whether the shapes of the multi-ringed disks of our sample can be understood in terms of dust trapping by gap-opening planets. In another companion paper [**Dullemond et al. REF**] we studied the trapping of dust in individual rings, for the five sources for which the rings are most prominent and isolated (AS 209, Elias 24, HD 163296, GW Lup and HD 143006). The gas pressure bumps were parameterized in that paper, and the total amount of dust that was trapped was directly fitted from the observations. This modeling strategy gives insight in the dust trapping and it was found that the parameters that fit the observations for these rings are partly degenerate, i.e. multiple parameter sets can fit the single dust traps equally well. In spite of this, some parameters could be constrained to a certain extent. The models of that paper could not, however, treat the global disk and dust behavior. It can therefore not answer questions such as: Will there be enough dust in the first place to be trapped? In multiple-ringed sources: will all dust get trapped in a single ring or, as the observations show, equally much in both rings? Can the planet gap opening scenario explain the dust rings we see, and if so, for which planetary masses?

While the paper by [**Zhu et al. REF**] focuses on the detailed 2-D dynamics of the planets, the gas and the dust, the present paper focuses on the long term behavior of the dust and the disk, while simplifying the model to 1-D.

2. Disk and dust evolution model

Models of dust drift and trapping in disks with planetary gaps require, strictly speaking, at least 2-D hydrodynamics models, because the process of gap opening as well as the dynamics of dust particles in the coorbital region of the disk are fundamentally 2-D/3-D processes. In a companion paper (Zhu et al. [**REF**]) the problem is indeed addressed in this way. Compared to the simplified model of the present paper, this 2-D method produces more realistic results and can handle any potentially non-axially symmetric structures. Indeed, even some of the sources with the most strongly pronounced ring structures in our ALMA LP sample feature blobs that break the axial symmetry. The drawback of this multi-dimensional modeling method is that it is relatively expensive due to the large number of orbits that have to be modeled. Parameter studies are therefore somewhat limited. In the present paper we follow therefore a method that is complementary to the 2-D hydrodynamics method. We assume axial symmetry. We follow the viscous disk equations with radial dust drift and mixing, and implement the planeteary gaps using a parameterized model described in Section 3. While this model will not be able to predict non-axially symmetric structures, it is extremely cheap: each model takes only a few seconds on a single core, for the entire disk ($0.1\,\mathrm{au} \lesssim r \lesssim 1000\,\mathrm{au}$) for its entire life time ($\mathrm{few}\times 10^6\,\mathrm{yr}$). This allows vast parameter scans.

Our model is a standard viscous disk accretion model with dust drift and mixing. Such models have been described in numerous papers before. We use the publicly available `DISKLAB` Python package[1] for this, which solves these equations using an efficient implicit differencing scheme. We refer to the corresponding paper [**DISKLAB paper ref**] for details.

For part of our models we simply prescribe a global dust size distribution. But we also run models with the two-pop-py recipe for dust growth (Birnstiel et al. 2012).

[1] **URL TO DISKLAB HERE**

3. Parameterized planet gap model

Since we cannot self-consistently model the gap opening in an axially symmetric disk model, we employ a parameterized gap model. There are several such gap models in the literature (e.g. Crida & Morbidelli 2007; Duffell 2015). We employ our own model, described in [**Zhang et al. REF**], which is valid also for low turbulent viscosity.

It should be noted, that planet-disk interaction not only changes the shape of the disk, but also leads to angular momentum exchange between planet and disk material. This means that the planet will migrate. Another consequence is that in the viscinity of the planet the viscous disk equations of the model do not correctly describe the disk. [**Describe the way we implement this**]

[**So far in DISKLAB any gap is implemented by adapting the viscosity. But perhaps it is better to develop a way to derive the planet-torque based on the parameterized profile. We can then even check if the torque matches the torque on the planet as derived directly from the hydrodynamics.**]

4. Comparison to the 2-D models

Before we can apply the 1-D axially symmetric model, we have to investigate how good this approximation is. To this end, we compare our results to the results from [**Zhu et al.**].

[**TODO**]

5. Model fitting procedure

Here we describe how we scan parameter space. This is not easy given the many parameters. We may wish to fix a few parameters and see how the model fits by varying the others.

6. Results

7. Conclusions

References

ALMA Partnership, Brogan, C. L., Pérez, L. M., et al. 2015, ApJL, 808, L3
Andrews, S. M., Wilner, D. J., Zhu, Z., et al. 2016, ApJL, 820, L40
Birnstiel, T., Klahr, H., & Ercolano, B. 2012, A&A, 539, A148
Bitsch, B., Lambrechts, M., & Johansen, A. 2015, A&A, 582, A112
Cieza, L. A., Casassus, S., Pérez, S., et al. 2017, ApJL, 851, L23
Crida, A. & Morbidelli, A. 2007, MNRAS, 377, 1324
Dipierro, G., Ricci, L., Pérez, L., et al. 2018, MNRAS, 475, 5296
Duffell, P. C. 2015, ApJL, 807, L11
Fedele, D., Carney, M., Hogerheijde, M. R., et al. 2017, A&A, 600, A72

Huang, J., Andrews, S. M., Cleeves, L. I., et al. 2018, ApJ, 852, 122
Isella, A., Guidi, G., Testi, L., et al. 2016, Physical Review Letters, 117, 251101
Lambrechts, M., Johansen, A., & Morbidelli, A. 2014, A&A, 572, A35
Paardekooper, S.-J. & Mellema, G. 2004, A&A, 425, L9
Rice, W. K. M., Armitage, P. J., Wood, K., & Lodato, G. 2006, MNRAS, 373, 1619