Project C1:

Trapping the dust:
Planet formation 'hotspots' in TDs

Authors:

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Requested positions: 1 PhD student

Abstract:
Based on our current understanding of the physics of planet formation, several processes seemingly prevent or stall the growth towards larger bodies: (1) collisional growth is inefficient above $\sim$meter-sizes, (2) fast radial migration removes solid particles on very short time scales, (3) large particles need to locally accumulate above the canonical dust-to-gas ratio in order to trigger gravoturbulent formation of planetesimals, and (4) radial migration of pebble-sized particles renders the accretional growth of planetesimals inefficient. Observations of transition disks suggest that they provide the environments, where all of these issues can be solved: trapping and growth of solid particles in the pressure bumps of transition disks can provide the large enough particles at high enough densities to trigger gravoturbulent planetesimal formation. Additionally, the trapped particles are not drifting away, meaning they can be efficiently accreted onto the growing planetesimals. It is the goal of this proposal to investigate the trapping, planetesimal formation, and planetesimal growth processes in these apparent 'planet formation hotspots' in transition disks.

1. State of the art and preliminary work

State of the art: Transition Disks and Planet Formation

With over to 3000 detected planets, it is striking that we still do not understand how planets form. Their building blocks, the *planetesimals* form in gas disks around young stars, where colliding dust grains form ever-larger aggregates. But this growth is not without limits: larger particles quickly drift towards the star and collide at speeds that shatter them to pieces, long before gravity can bind them together. The mechanisms involved in the assembly and transport of these building blocks remain some of the biggest mysteries of planet formation.

Over the last couple of decades, observations of protoplanetary disks have revolutionized the field of planet formation. This started with surveys of disks (see the review of Williams & Cieza 2011) and continued with ever better imaging campaigns (e.g., Andrews & Williams 2007; Brown et al. 2009, and many others). Early imaging results of Brown et al. (2008) and Brown et al. (2009) revealed for the first time depleted inner cavities in disks that were previously just suspected from the spectral energy distributions. These disks with holes were initially thought to be in the process of transitioning from a gas rich disk to a gas poor disk (e.g., Clarke et al. 2001) and thus termed *transition disks* (see Espaillat et al. 2014; Alexander et al. 2014, and references therein).

As statistics and theoretical models improved, it became clear that this cannot be the full story: some

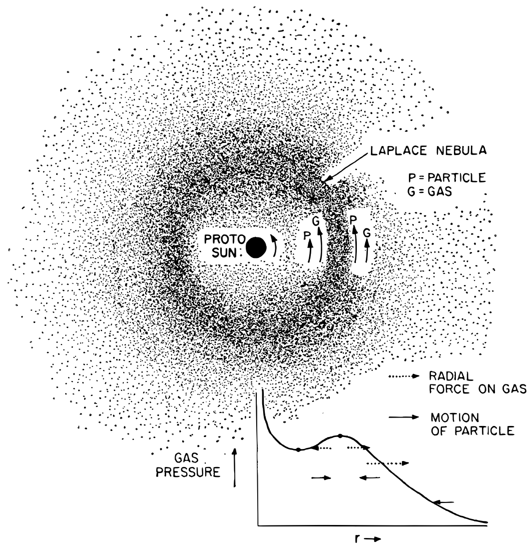

Figure 1: Accumulation of solid particles in pressure bumps. Taken from Whipple (1972).

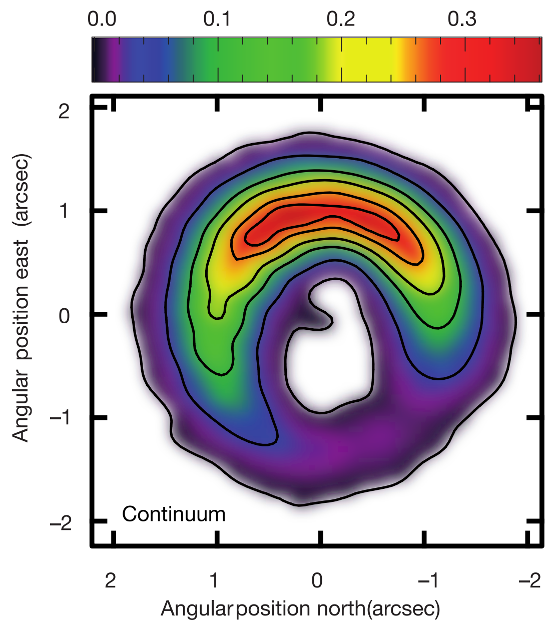

Figure 2: Early imaging of ring-like accumulations of dust in the transition disk SR 21N. Taken from Brown et al. (2009). Units are in Jy/beam. **XXX update caption and all references XXX**

of the inner holes were found to be clearly too large and the disk accreting too vigorously to be explainable by current models of photoevaporation (i.e. Type 2 TDs, Owen et al. 2010, 2011). Other explanations were discussed, such as particle growth (Dullemond & Dominik 2005; Tanaka et al. 2005; Birnstiel et al. 2012a) or gap opening by planets (Paardekooper & Mellema 2004, 2006; Rice et al. 2006; Pinilla et al. 2012a; Zhu et al. 2012). Most of these models have in common that some mechanism (e.g., photoevaporation, planet-disk-interaction, or others) produce a pressure maximum. Solid particles that have collisionally grown to macroscopic sizes experience fast radial migration towards higher pressure (Whipple 1972; Weidenschilling 1977; Nakagawa et al. 1986). Already Whipple (1972) suggested that particles moving due to this effect can become *trapped* in a pressure maximum, as depicted in Figure 1 taken from his paper. One of the first images of such a ring-like transition disk, from Brown et al. (2009) is shown in Figure 2.

Statistical analysis of the occurrence rates and properties of transition disks suggested that there are two families of transition disks: a family of small accretion rate / small hole sizes / small disk mass and another family of larger hole sizes accompanied by larger disk masses and higher accretion rates (Owen & Clarke 2012). While the possibly diverse *origins* of transition disks are still obscure, the observations at face value already show us something even more interesting: large fractions of the solid contents of the disks can be contained near the inner edge of the outer disk. These cavity edges should therefore be prime regions for the formation of planetesimals or even planets. As such, transition disks are not only interesting probes of disk evolution or disk dispersal, but may allow us to study in detail what role pressure bumps are playing in the formation of planets.

In 2013, we proposed that the dust trapped in a slightly lopsided gas disk (i.e. an azimuthal pressure bump) can become extremely concentrated in that azimuthal over-density (see Birnstiel et al. 2013). In the same year, we were part of a team that published and analyzed ALMA observations of the disk Oph IRS 48 that showed such an extreme asymmetry, as predicted by the models (see van der Marel et al. 2013). It is widely accepted that the dust accumulations in pressure bumps (whatever their formation mechanism may be) are prime regions – *hot spots* – of planet formation: accumulation of particles in pressure bumps (e.g., Kretke & Lin 2007) prevents them from drifting away and shortens the growth time scales of dust particles allowing further growth (Brauer et al. 2008b). Accumulation of these particles can trigger the streaming instability which needs particle accumulations and particles of the right sizes to operate (Youdin & Goodman 2005; Johansen et al. 2007). Vortices further support the accumulation to critical densities (Barge & Sommeria 1995; Klahr & Henning 1997; Raettig et al. 2015) or even the direct formation of earth sized objects (Lyra et al. 2009).

Another revolution in the field of planet formation came not from the observational, but from the theoretical side. It was shown that small particles can very effectively be accreted onto planetesimals under the right conditions when gas drag effects increase the effective cross section of the accreting body (Ormel & Klahr 2010; Lambrechts & Johansen 2012). It has turned out that this process – termed *pebble accretion* – can be dominant over the late-stage oligarchic growth and giant impact growth if the flow of pebbles can be controlled (Levison et al. 2015), although the exact ratio of mass that is accreted via planetesimals and via smaller particles is still under investigation, as is the efficiency of the process (see Guillot et al. 2014; Visser & Ormel 2016; Owen & Kollmeier 2016). But there is a problem with this and that is the fact that planetesimals seem to be formed big (Morbidelli et al. 2009, Klahr et al., submitted to Nature) with sizes around 100 km. This happens to be the size at which pebble accretion onto the planetesimals is particularly inefficient (Visser & Ormel 2016).

In other words: planetesimals likely form 100-km-sized bodies, but only if over-densities of pebble sized objects are present. Further growth of planetesimals of this size is inefficient unless there is a large reservoir of particles of the right sizes available to be accreted. Pressure bumps, such as the ones observed in transition disks provide the right conditions to solve both of these problems.

Several authors have already investigated the dynamics of particles in and around planetary gaps in disks. Some of the recent work includes Paardekooper & Mellema (2004, 2006), Rice et al. (2006), Lyra et al. (2009), Zhu et al. (2012), Gonzalez et al. (2012), Ataiee et al. (2013), or Picogna & Kley (2015), to name just a few. Most of these works have in common, that they follow only small particles that are not growing in size and they do not follow planetesimals or their growth at the same time. These works are mainly aimed at explaining the observed properties of transition disks, but surprisingly little work has been done to understand how transition disks – or pressure bumps in general – regulate the formation of planets or planetesimals. Some authors (e.g., Chatterjee & Tan 2014, and following papers in that series) have pointed out how pressure bumps and planet formation can trigger each other, leading to a inside-out planet formation scenario. This is a promising scenario to explain for example the systems with tightly packed inner planets discovered with the Kepler Mission (Fang & Margot 2012). However the details of what happens to the dust and larger bodies in the pressure bump has not been subject of a dedicated study yet.

With this proposal, we want to build on our expertise on dust evolution and particle trapping in protoplanetary disks to study the formation of planetesimals in pressure bumps, their further evolution due to dynamics, interaction with the gas disk, interaction with other planetesimals, and growth due to accretion of pebbles.

The goal of this proposal is to understand how planetesimal and planet formation proceeds in pressure bumps and to find out if transition disks are indeed the hot-spots of planet formation that we think they are.

Preliminary Work

Both PIs have extensive experience in the physics of particle growth and dynamics of dust particles (e..g Dullemond & Dominik 2005; Brauer et al. 2008a; Zsom & Dullemond 2008; Birnstiel et al. 2010, 2012b; Drążkowska & Dullemond 2014, see Birnstiel et al. 2016 for a recent review) as well as in disk structure and evolution (e.g., Dullemond et al. 2001, 2002; Dullemond & Dominik 2004; Dullemond

& Monnier 2010; Birnstiel et al. 2015, and many others). Furthermore, C.P. Dullemond has been supervising or contributing to several works on planet-disk-interaction, vortex-formation, and planet-vortex-interaction (Regály et al. 2012; Ataiee et al. 2013, 2014).

More recently, a collaboration between the PIs of this proposal and the group of Dr. Hui Li at Los Alamos National Labs (LANL), USA has been established. Dr. Hui Li has been pioneering the field of vortex formation in the context of protoplanetary disks (Li et al. 2001, 2000). Furthermore, the LANL group has extensive experience in hydrodynamical modeling and more recently in modeling dust dynamics via tracer fluids (e.g., Fu et al. 2014; Jin et al. 2016).

Dr. T. Birnstiel has worked on two-dimensional models of dust evolution, treating particle growth, fragmentation, turbulent mixing and vertical settling. Preliminary results of this are shown in Figure 3 in the left column. Similar work on this, but in the radial/azimuthal dimensions is ongoing as part of the collaboration with the LANL group. The right hand side panels in Figure 3 show a proof of concept simulation where gas dynamics as well as dust dynamics of around 100 different particle sizes are taken into account. Subroutines for simulating particle growth and fragmentation have been developed and are currently being tested.

To continue this work on particle growth in two dimensions as well as work on other related topics, Dr. T. Birnstiel has recently been awarded an *ERC Starting Grant* which will start in March 2017 at the LMU Munich. By becoming part of this Research Unit, Dr. Birnstiel will share the progress and the resulting data with the research group wherever other projects of the Research Unit profit from it. This includes, but is not limited to, the dust density distribution $\rho_{\rm dust}(r, z, a)$ as function of distance to the star r, height above the mid-plane z, and particle size a and similar results from the radial/azimuthal models.

1.1 Project-related publications

Birnstiel, T., **Dullemond, C.P.** & Brauer, F., *Gas and dust evolution in protoplanetary disks*, 2010, A&A 513, 79. In this paper we present the basic code for the evolution of the disk and the dust. The latter follows the dust coagulation, fragmentation, settling and radial drift of the dust.

Sándor, Z., Lyra, W., **Dullemond, C.P.**, *Formation of PlanetaryCores at Type I Migration Traps*, 2011, ApJ, 728, L9. Here we performed detailed N-body calculations of multi-planet systems with migration torques. This experience helps us with determining the dynamics of pebbles as they approach the planet. The migration torque is then replaced by gas friction.

Birnstiel, T., Klahr, H. & Ercolano, B.: *A simple model for the evolution of the dust population in protoplanetary disks*, 2012, A&A 539, 148. In this model the flow of pebbles from the outer disk regions into the inner planet forming disk regions is studied, and an easy to use model derived.

Birnstiel, T., Andrews S.M., Ercolano B. *Can grain growth explain transition disks?*, 2012, A&A, 544, A79. We showed that particle coagulation in itself can successfully create observed transition disk signatures at infrared wavelengths, but fails to produce the central cavities at (sub-)millimeter wavelengths.

Pinilla P., Benisty M., **Birnstiel, T.** *Ring shaped dust accumulation in transition disks*, 2012, A&A, 545, A81. We presented the first model that explained transition disks trough a combination of particle growth and transport processes and the pressure trap created by a giant planet.

Ataiee, S., Pinilla, P., Zsom, A., **Dullemond, C. P.**, Dominik, C., Ghanbari, J. *Asymmetric transition disks: Vorticity or eccentricity?*, 2013, A&A, 553, L3. We demonstrated how asymmetries in dust disks can be produced by vortices or by disk eccentricity and how these methods cause very different dust density contrasts.

van der Marel N., van Dishoeck E.F., Bruderer S., **Birnstiel, T.**, Pinilla P., **Dullemond, C.P.**, et al.: *A Major Asymmetric Dust Trap in a Transition Disk* 2013, Science, 340(6), 1199. First observation of an extremely lopsided dust disk that was interpreted as trapping of solids in a vortex-like structure.

Ataiee, S., **Dullemond, C. P.**; Kley, W., Regály, Zs., Meheut, H. *Planet-vortex interaction: How a vortex can shepherd a planetary embryo*, 2014, A&A, 572, A61. We studied how a vortex interacts gravitationally with a migrating planet or with a planet that is created inside the vortex.

Pinilla, P., Klarmann, L., **Birnstiel, T.**, Benisty, M., Dominik, C., **Dullemond, C.P.** *A tunnel and a traffic jam: How transition disks maintain a detectable warm dust component despite the presence of a large planet-carved gap*, 2016, A&A 585, A35. Here the dust coagulation and trapping model is extended to explain the shape of pre-transitional disks via incomplete trapping, coagulation and fragmentation near the water ice line.

2. Objectives and work programme

2.1 Anticipated total duration of the project

36 Months

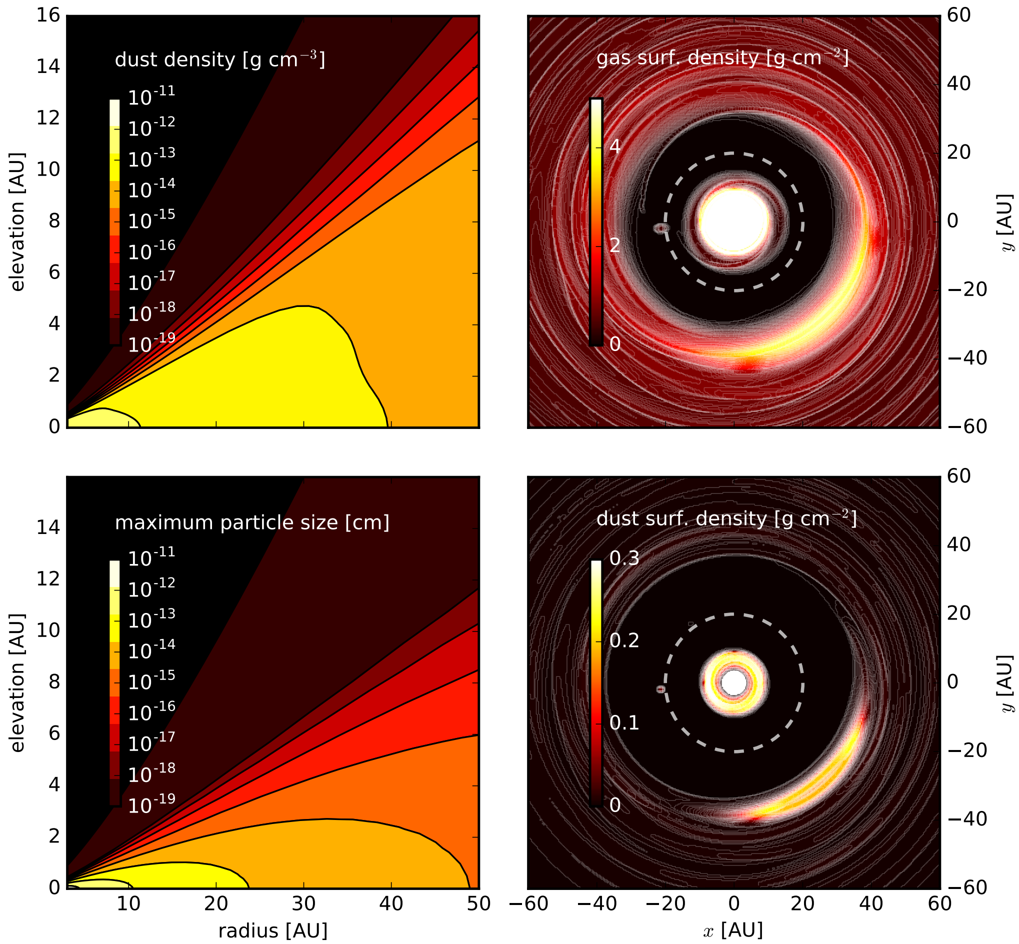

Figure 3: Proof-of-concept models for 2D dust evolution simulations. The panels to the **left** show the radial/vertical distribution of solids (**top**) and maximum particle sizes (**bottom**) where both coagulation and vertical transport processes are treated at each point of a 2D grid. The panels on the **right** show radial/azimuthal results of the LA-COMPASS code (in normalized code units, resolution of 1024×1536) that is now able to treat 100s of particle sizes and their size evolution. The **top** panel shows the distribution of gas surface density where a planet, orbiting on the dashed line, carves a gap and forms a pressure bump outside of its orbit. The pressure bump becomes Rossby unstable and the resulting vortex efficiently traps larger particles. The distribution of 0.09 mm sized particles is shown in the **lower right**.**XXX Fix lower left color bar XXX**

2.2 Objectives

The goal of this project is to investigate the growth and dynamics of planetesimals and of forming planets in pressure bumps of transition disks. The scientific questions we want to answer are:

- How effectively can planetesimals be formed in pressure bumps?
- What properties of the pressure bumps are compatible with observational properties of protoplanetary disks? How effective can planet(esimal) formation be in transition disks? At what efficiency will it start violating observational properties of observed disks?
- Is growth via mutual collisions or accretion of pebble sized dust the dominant mode of planetesimal growth?
- What role does the dynamical evolution play – how large can planetesimals grow before their dynamics either leads to destruction or causes them to leave their birth places? Related: how will a newly formed planet in the bump move around the remaining pebbles? Will there be observational signals of such a planet in the shape of the dust concentration and its polarized signature (see, e.g., Kataoka et al. 2016)?
- How does the origin of the pressure bump (e.g. viscosity bump, photoevaporation, or planet) affect these scenarios?
- How does the situation change with various parameters such as the extent of the pressure bump, the turbulence strengths or in particular with vortices in case the pressure bump becomes Rossby wave unstable?

2.3 Work programme including proposed research methods

2.3.1 Research Methodology

In this project, we will couple the evolution of small solid particles via recipes of gravoturbulent planetesimal formation to the growth and dynamical evolution of planetesimals. To do this, we will will employ two different methodologies: first, we will use simplified gas disk structure models (i.e. hydrostatic disks). Therefore, we will be able to concentrate on the dust processes and the planetesimal formation and dynamical evolution processes in more detail. This methodology will encompass phase I and II (cf. Section 2.3.3.1 and Section 2.3.3.2). The second approach in phase III (cf. Section 2.3.3.3) will include detailed hydrodynamical processes but therefore necessarily simplifying other aspects such as the dust evolution. This simplification, however, will be based on the results of phase I and II (and the ERC project of Dr. Birnstiel) and will thus *not* be based on ad-hoc assumptions.

2.3.2 Research Tools and Inputs

For this project, we will be using the following tools:

- A dust evolution code, either the open-source code `twopoppy` (Birnstiel et al. 2012b), described below, or if needed, the gas+dust disk evolution code of Birnstiel et al. (2010).
- A N-body integrator. For this we will the open-source code `REBOUND`, which offers a wide variety of integration schemes and flexible options to include additional forces or add/remove particles.
- A disk hydrodynamical code with Lagrangian particles. The foundation of this will be the custom version of the `PLUTO` code from (Picogna & Kley 2015). We will use this code or future versions of it in phase III (Section 2.3.3.3) and implement the growth processes developed in phase I and phase II.

- For comparison with dust continuum observations, we will employ the 3D monte carlo radiative transfer code `RADMC-3D` that was developed by the co-PI Prof. Dullemond. Scripts to directly run the `RADMC-3D` dust radiative transfer calculation with the input from the dust evolution code of co-PI Dr. Birnstiel are available. These include opacity calculations as well as hydrostatic equilibrium iteration with dust-settling-mixing solutions for each particle size.

2.3.3 Research Plan

2.3.3.1 Phase I: Planetesimal formation and simple gas structures

The student will begin by getting acquainted with the astrophysics of disks and planet formation on the one side and and with the numerical methods on the other side. The initial setup will be an axisymmetric pressure bump profile. For this, we will start with a parametrized, stationary pressure bump in our one dimensional dust/gas code `twopoppy`[1] (Birnstiel et al. 2012b). Further gradual improvements will include an α-disk evolution (already implemented in the code) where the pressure bump forms due to parametrized variations in the α-viscosity (Kretke & Lin 2007). This will allow us to look at time-dependent trapping processes, e.g. for pressure bumps with a finite life time. If necessary, the viscous radial evolution of the gas density could also be treated using 1D hydrodynamics to account for deviations in the rotation profile near the bump.

The student will then implement a subroutine that converts small dust particles to planetesimals whenever the right conditions are fulfilled. Similar methods have already been used by the PIs (Drążkowska & Dullemond 2014, and Klahr, Birnstiel, Lenz, in prep.). We will use Eq. 12 of Drążkowska & Dullemond (2014), which is a fit to detailed numerical results of Bai & Stone (2010) consistent with other works on planetesimal formation in the context of the streaming instability (e.g., Johansen et al. 2009b). Based on the local metallicity and the resulting planetesimal formation efficiency, dust mass will be removed via a sink term and the resulting mass in planetesimals will be tracked (without further evolution of the planetesimals at this point). The particle size distribution can be reconstructed using the methods published in Birnstiel et al. (2015). Should we find that the accuracy of this method is not sufficient (i.e. if the results are very sensitive to one of the approximations done here), then we could switch to an implementation of the code presented in Birnstiel et al. (2010). This will be more accurate and more detailed, but also significantly slower but not prohibitively slow as the N-body dynamics of the later stages of the project will be more limiting. The calculations outlined above will lay the foundation of the next parts of the proposed research plan:

- They provide the accretion rate of dust particles into the pressure bump.
- They provide the size distribution of the particles entering the pressure bump.
- The subroutine will calculate how much of the available dust is transformed into planetesimals.

Using the code at this stage, we will already be able to publish a first paper describing the methods and our results on planetesimal formation rates comparing to previous works in this direction (e.g., Drążkowska & Dullemond 2014; Krijt et al. 2016). Some mechanisms creating pressure bumps have a finite life time, such as zonal flows, or pressure bumps at the edges of dead zones. Using bumps of finite life time will allow us to investigate the efficiency of particle trapping in time-dependent pressure maxima and their possible relation to Type I transition disks, which is a significant improvement over previous works such as Pinilla et al. (2012b) and Pinilla et al. (2013). By linking this to existing millimeter wave radio-surveys (e.g., Pascucci et al. 2016 and references therein as well as previous surveys such as Ricci et al. 2010) we will be able to test which bump amplitudes, bump sizes, and life times are producing results consistent with (1) dust continuum observations and (2) dust disk life times. This way, we will be able to exclude or constrain some of the theoretically proposed mechanisms, such as zonal flows (e.g., Johansen et al. 2009a; Dittrich et al. 2013; Bai & Stone 2014).

[1] `http://birnstiel.github.io/two-pop-py/`

2.3.3.2 Phase II: N-Body dynamics and planetesimal evolution

In Phase I, planetesimals are formed at a given rate based on calculations of the dust evolution code, however the forming planetesimals are just kept on record and are not evolving further. Phase II of this proposal aims at improving upon this. At the beginning of the project, we will use the modular, and easy to use N-body integrator `REBOUND`[2] (Rein & Liu 2012). The fact that both `twopoppy` and `REBOUND` have python interfaces simplifies linking them: based on the planetesimal formation rates and the gas and dust surface densities from `twopoppy`, particles (planetesimals) can be created in `REBOUND`. Initially, planetesimals might be tracked individually, but as their number increases, we will likely need to switch to a super-particle approach, where one individual particle in the code represents a larger number of physical planetesimals.

The gas and dust density distribution is still assumed to be axisymmetric at this point, but an analytical vertical distribution of the density will be assumed to create a 3D density distribution: the gas will be assumed to be in hydrostatic equilibrium, while the dust will be in a mixing-settling equilibrium (Fromang & Nelson 2009).

At this point of the proposal, there are two parallel directions in which the simulation tools will be improved, linking to two different scientific directions: one focuses on more detailed gas dynamics that has links to project C2 and will be discussed below in Section 2.3.3.3. In this phase II of the research plan we will focus on the N-body treatment of the planetesimals and related science questions (to clarify: pebbles are treated as a fluid).

Based on the dust particle sizes and the 3D distribution of dust and gas developed above, we can calculate the accretion rate of pebbles onto the planetesimals. This will use the prescriptions of Ormel & Klahr (2010), Visser & Ormel (2016) and related works. Based on these rates, calculated/updated at appropriate time intervals, the mass of the N-body particles (in the `REBOUND` code) will be increased and the total mass of accreted dust particles will be removed as sink terms in the `twopoppy` code. This way the evolution of planetesimals and of the dust distribution affect each other:

Planetesimals (1) form based on the local metallicity and (2) grow via pebble accretion of dust particles of the right sizes. Dust, on the other hand, is removed by both of these effects, but possibly and to a smaller extend replenished by fragments. If these dust removal processes are efficient no further planetesimals will be formed since the metallicity in the bump will be kept below critical values. As another consequence, the reduction in dust mass might also reduce the particle sizes which further minimizes the amount of particles contributing to planetesimal formation. This latter effect will, however also decrease the efficiency at which the dust is accreted onto the planetesimal. Based on this, various outcomes of the early stages of planet formation could be imagined:

- Planetesimals form but then prevent further planetesimal formation, instead efficiently growing via pebble accretion (and possibly oligarchic growth at the same time).
- Planetesimal formation may be too efficient: many planetesimals form leaving little amounts of dust to be accreted onto the planetesimals. At this point dynamical and collisional evolution of planetesimals may become the dominant driving force.

As this shows, it will be extremely interesting to see how the formation of larger bodies proceeds in the hot-spots of planet formation in transition disks. This project so far already incorporates aspects of gas dynamics, collisional evolution and dynamics of small dust particles and N-body dynamics, a seemingly challenging combination. However, we would like to point out that the methods and codes we use for this are well established: the `REBOUND` code for example allows scientifically relevant calculation with only a few lines of code. It offers a wide variety of well tested and well documented integrators and a simple object-oriented approach to handle additional forces or close encounters. The `twopoppy` code as well can be run with only a hand full of lines of code and well reproduces the results of complicated coagulation codes. Combining these codes offers a student interesting quick

[2] `http://github.com/hannorein/rebound`

successes but still the opportunity to gradually learn the numerical methods and also the physical processes used and assumed "under the hood" of these codes.

At the end of this phase II of the project, we anticipate at least one more publication that describes the numerical setup and explains the findings of a parameter study. With this study, we will be able to calculate planetesimal formation rates under various trapping conditions and study how the general outcome but also the detailed size distribution of planetesimals varies with disk parameters. We will also test under which conditions an analytical treatment of the involved effects, based on rate equations, can be found. Follow up studies can include improved collision models, effects of turbulence on the planetesimal distribution and many other effects.

2.3.3.3 Phase III: Breaking the Symmetry

So far the distribution of both dust and gas has been assumed to be symmetric. As observations show us, this is indeed the case in many transition disks, as well as in disks with small scale axisymmetric structure, such as HL Tau (ALMA Partnership et al. 2015; Carrasco-González et al. 2016), TW Hydrae (Andrews et al. 2016; Tsukagoshi et al. 2016), or HD 97048 (van der Plas et al. 2016). These observations prove that the approach of the phases I and II of this project is extremely relevant. However, other observations spectacularly show strong asymmetries in the dust continuum emission (e.g., Casassus et al. 2013; van der Marel et al. 2013). It is suspected that these asymmetries arise from a strong pressure bump which can become unstable to the Rossby instability (e.g., Li et al. 2001; Lyra et al. 2009). The resulting vortex then represents an azimuthal pressure maximum and is therefore able to azimuthally trap particles, further concentrating them (e.g., Barge & Sommeria 1995; Klahr & Henning 1997; Lyra et al. 2009; Birnstiel et al. 2013; Lyra & Lin 2013). In this phase III of the project, we therefore want to study the formation of planetesimals and their growth towards larger bodies in non-axisymmetric disks. This opens the possibilities to study a wide range of interesting scenarios:

First of all, it allows to study how the formation of a vortex in a pressure bump changes the outcome from phase II: is planetesimal formation more efficient inside a vortex? If so, are planetesimals growing by pebble accretion less efficient compared to a symmetric pressure bump? How does the ratio between planetesimal formation rate and planetesimal growth rate change if a vortex is formed? How are the planetesimal dynamics changing from the gravitational interaction with the vortex?

Secondly, the (at least) three possible origins of the pressure bump can make a difference:

1. How does a viscosity transition (via turbulence) affect the formation and growth rates as well as the dynamical / collisional evolution?
2. How does the gravitational forcing of a giant planet influence the dynamics of either the dust or the planetesimals?
3. Is a pressure bump caused by photoevaporation more closely resembling item 1 or 2 or entirely different?

Can we find structural differences that allow us to observationally distinguish between the possible causes of a pressure bump?

The main addition in this phase III of the project is the hydrodynamical aspect where we switch from a quasi-stationary disk structure to actual hydrodynamics. While this opens an enormous range of interesting topics to investigate, it comes at significant numerical changes and challenges that make this the most risky part of the project. However, we would like to stress, that the thesis of the PhD student is not decisively dependent on this part of the project. Even if this phase III turns out to be numerically too challenging or cannot be finished within the duration of the PhD program, phase I and II offer plenty of applications and publications for a PhD thesis.

The addition of hydrodynamics cannot be easily added on top of the python code that employs `REBOUND` and `twopoppy`. Furthermore, long integration times of 2D hydrodynamical simulations are computationally very expensive, in particular if the dust phase and N-body particles are to be evolved at the same time. Therefore, complexity needs to be reduced in other aspects of the model. We will therefore simplify the treatment of dust coagulation: we will reduce the dust to a single fluid with either a fixed particle size that is representative of the particle sizes trapped in a pressure bump in phase I and II of this project. The best way in which this can be mimicked (for example using a radially varying particle size for the dust fluid) will be tested as part of the ERC project.

To treat the new aspects (2D hydrodynamics, 2D dust dynamics) we will switch to the `PLUTO` code[3]. Our collaborator, Prof. Kley and his former postdoc Dr. Picogna (now in the group of Prof. Ercolano) have developed a particle integrator for the `PLUTO` code (see Picogna & Kley 2015). Furthermore, the treatment of dust as a tracer is already implemented in `PLUTO` (although not yet officially supported, some testing will be needed). This part of the proposal will therefore be done in close collaboration with the Tübingen group and with members of the ERC group at Munich.

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2.4 Data handling

The model results of this project as well as the relevant results of the ERC group will be shared with other members of the Research Unit using the Research Units dedicated server.

Furthermore, we will publish all data, scripts, and where possible the simulation codes necessary to reproduce the results presented in the publications of this project. To this end we will either use available options of the publishers and/or use Zenodo[4] to ensure reproducibility, long-time availability, and the possibility to reference the data.

2.5 Other information

None

2.6 Information on scientific and financial involvement of international cooperation partners

None

3. Bibliography

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[3] `http://plutocode.ph.unito.it`
[4] Zenodo is a free open science repository funded and supported by the European Commission and managed by the CERN data center. See `https://zenodo.org`.

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4. Requested modules/funds

4.1 Basic Module

4.1.1 Funding for Staff

We request funding for 1 PhD position to be stationed at the **XXX XXXX XXX**.

4.1.2 Direct Project Costs

4.1.2.1 Equipment up to EUR 10,000, Software and Consumables

Theoretical numerical research can only be done when sufficient and appropriate computational facilities are available. While production runs will be done on supercomputer facilities, a substantial part of the work in this project is code development. Testing these codes on realistic problems requires a workstation for each of the two PhD students – which is beyond the standard base equipment (Grundausstattung). We therefore request a workstation-grade desktop computer for the PhD position for 4 000 €.

4.1.2.2 Travel Expenses

Participation at at least one conference, winter school, or similar is anticipated for the PhD student. The last year of the PhD project should also offer the opportunity to visit conferences and/or institutions in the US, hence the increased travel budget in year 3. In addition to travel funds for conferences for the PIs, regular mutual working visits at Heidelberg/Munich are planned, anticipating 1500 Euros per year.

	Year 1	Year 2	Year 3	Sum
Conferences PhD student	2000 €	2000 €	3000 €	7000 €
Conferences PIs	3000 €	3000 €	3000 €	9000 €
Mutual working visits HD/M	1500 €	1500 €	1500 €	4500 €
	6500 €	6500 €	7500 €	**20500 €**

4.1.2.3 Project-related publication expenses

We request 750 € per year (a total of 2250 €) for publication expenses.

5. Project requirements

5.1 Employment status information

Dr. Birnstiel, Tilman, ERC Starting Grant holder (starting: March 2017) at the Ludwig-Maximilians-Universität Munich. Hiring process for tenure-track W2 professorship at LMU Munich ongoing, anticipated starting date: February-March 2017
Prof. Dr. Dullemond, Cornelis Petrus. W3 Professor (permanent) at Heidelberg University.

5.2 First-time proposal data

N/A

5.3 Composition of the project group

Munich: Only the co-PI TB will work directly on the project; group members of the ERC Starting Grant group led by the co-PI will share results where needed.
Heidelberg: Only the co-PI CPD.
XXX Update if necessary XXX

5.4 Cooperation with other researchers

5.4.1 Planned cooperation on this project

5.4.1.1 Collaborating researchers for this project within the Research Unit

The student of this project, stationed in Munich, will greatly benefit from the numerical expertise within the Research Unit, in particular the hydrodynamical and N-body expertise in Tübingen and in Heidelberg. The simulation results and setups will also be exchanged with project C2 (PI Ercolano, Caselli) and the implications of the results, in particular, the radiative transfer model output, will be compared against available and upcoming observational campaigns of project A1 (PI Testi) and our external collaborators Prof. van Dishoeck and Prof. Henning. This will encompass modelled emission of both (sub-)mm continuum and scattered light. This project will also benefit from frequent exchange with projects D1 (PI Kley) and D2 (PI Dullemond) particularly the planet-disk interaction models and the Lagrangian particle modules for the `PLUTO` code. Vice-versa, D1 in particular will benefit from the dust and collision models created in this project.

5.4.1.2 Collaborating researchers for this project outside of the Research Unit

We will collaborate with the ERC-funded group of the PI Dr. Birnstiel, which will run parallel to the Research Unit.

5.4.2 Researchers with whom you have collaborated scientifically within the past three years

We list only true collaborations, not all co-authors on publications from large consortia.
S. Andrews (CfA, Harvard), S. Ataiee (Uni Bern), X.-N. Bai (CfA, Harvard), A. Banzatti (STScI, Baltimore), M. Benisty (IPAG, Grenoble), C. Brinch (University of Copenhagen), J. Carpenter (Caltech), C. Carrasco-González (UNAM, México), C. J. Chandler (NRAO, USA), E. Chapillon (Univ. Bordeaux), F. Ciesla (The University of Chicago), L. I. Cleeves (University of Michigan), E. Di Folco (Univ. Bordeaux), C. Dominik (University of Amsterdam), J. Drazkowska (Zürich University), A. Dutrey (Univ. Bordeaux), B. Ercolano (LMU München), M. Fang (Purple Mountain Observatory, China), M. Flock (JPL, Caltech), J. H. Girard (ESO, Chile), U. Gorti (SETI Institute), N. Grosso (Université de Strasbourg), G. Guidi (INAF Arcetri, Italy), S. Guilloteau (Univ. Bordeaux), Th. Henning (MPIA, Heidelberg), G. Herczeg (Kavli Institute Beijing), M. Hogerheijde (Leiden University), D. Hollenbach (SETI Institute), N. Huelamo (Centro de Astrobiología, Spain), A. Isella (Rice University), A. Johansen (Lund Observatory), A. Juhász (Institute of Astronomy, Cambridge), M. Kama (Leiden Observatory), A. Kataoka (Heidelberg University), H. Klahr (MPIA Heidelberg), L. Klarmann (University of Amsterdam), W. Kley (Universität Tübingen), R. Kuiper (Uni Tübingen), H. Linz (MPIA Heidelberg), H. Meheut (CEA, France), M. Min (University of Amsterdam), P. Mollière (MPIA Heidelberg), M. Momose (Ibaraki University), C. Mordasini (Universität Bern), R. Murray-Clay (UCSB), T. Muto (Kogakuin University), A. Natta (Dublin Institute for Advanced Studies), K. Öberg (CfA, Harvard), S.-J. Paardekooper (Queen Mary University of London), P. Pinilla (Leiden Observatory), A.-M. Piso (CfA, Harvard), V. Piétu (IRAM, France), A. Pohl (MPIA Heidelberg), K. M. Pontoppidan (STScI, Baltimore), L. Pérez (MPIfR Bonn), J. P. Ramsey (Copenhagen), Zs. Regály (Konkoly Observatory, Hungary), L. Ricci (CfA, Harvard), V. Roccatagliata (LMU, Munich), D. Semenov (MPIA Heidelberg), A. Sicilia-Aguilar (University of St Andrews), S. Stammler (Heidelberg University), M. Tazzari (ESO), R. Teague (MPIA Heidelberg), L. Testi (ESO), C. Thalmann (ETH Zurich), J. Tobin (Leiden Observatory), N. Turner (JPL, Pasadena), T. Tsukagoshi (Ibaraki University), N. Turner (JPL, Pasadena), A. Uribe (Coll. Charlston), C. Walsh (Leiden Observatory), D. Wilner (CfA, Harvard), Z. Zhu (Princeton University), J. de Boer (Leiden Observatory), M. de Juan Ovelar (Liverpool John Moores University), R. van Boekel (MPIA Heidelberg), E. F. van Dishoeck (Leiden Observatory), T. van Kempen (Leiden Observatory), N. van der Marel (Leiden Observatory)

5.5 Scientific equipment

At ZAH we have access to the bwFor cluster at Tübingen. All members stationed at LMU will have access to high performance computing clusters at the Leibnitz Rechenzentrum (`lrz.de`).

5.6 Project-relevant interests in commercial enterprises

None

5.7 Additional information

None