# Project C1: Trapping the dust: Planet formation 'hotspots' in TDs

**Authors:**

| | |
|---|---|
| PIs: | T. Birnstiel (LMU) |
| | C.P. Dullemond (U. Heidelberg) |
| Co-I: | W. Kley (U. Tübingen) |
| Collaborations: | van Dishoeck (Leiden/MPE) |


**Requested positions: 1 PhD student**

**Abstract:**

**XXX Text XXX**

## 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 **?**) and continued with ever better imaging campaigns (e.g., **??**, and many others). Early imaging results of **?** and **?** 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. **?**) and thus termed *transition disks* (see **??**, and references therein).

As statistics and theoretical models improved, it became clear that this cannot be the full story: some 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 (**??**). Other explanations were discussed, such as particle growth (**???**) or gap opening by planets (**?????**). 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 (**???**). Already **?** suggested that particles moving due to this effect can become *trapped* in a pressure maximum, as depicted in Fig. 1 taken from his paper. One of the first images of such a ring-like transition disk, from **?** is shown in Fig. 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

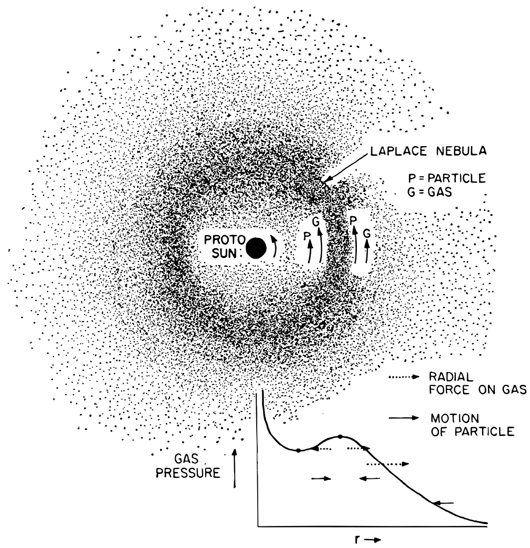


Figure 1: Accumulation of solid particles in pressure bumps. Taken from **?**.

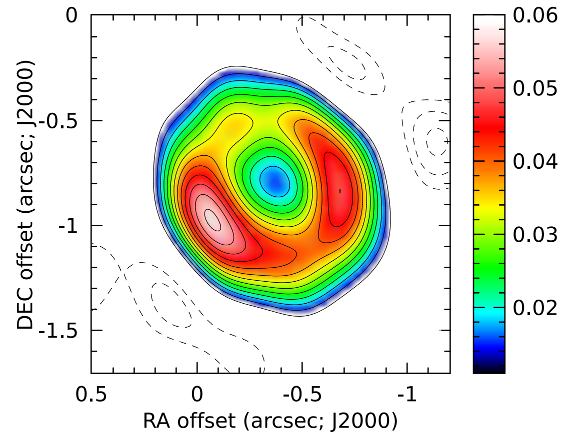


Figure 2: Early imaging of ring-like accumulations of dust in the transition disk SR 21N. Taken from **?**. Units are in Jy/beam.

(**?**). 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 **?**). 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 **?**). 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. **?**) prevents them from drifting away and shortens the growth time scales of dust particles allowing further growth (**?**). Accumulation of these particles can trigger the streaming instability which needs particle accumulations and particles of the right sizes to operate (**??**). Vortices further support the accumulation to critical densities (**???**) or even the direct formation of earth sized objects (**?**).

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 (**??**). 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 (**?**), 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 **??**). But there is a problem with this and that is the fact that planetesimals seem to be formed big (**?**, 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 (**?**).

*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 **??**, **?**, **?**, **?**, **?**, or **?**, 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. **?**, and following papers in this 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 (**?**). 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 **??????**, see **?** for a recent review) as well as in disk structure and evolution (e.g. **?????**, 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 (**???**).

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 (**??**). Furthermore, the LANL group has extensive experience in hydrodynamical modeling and more recently in modeling dust dynamics via tracer fluids (e.g., **??**).

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 Fig. 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 Fig. 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 $\rho_{\mathrm{dust}}(r, z, a)$ 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

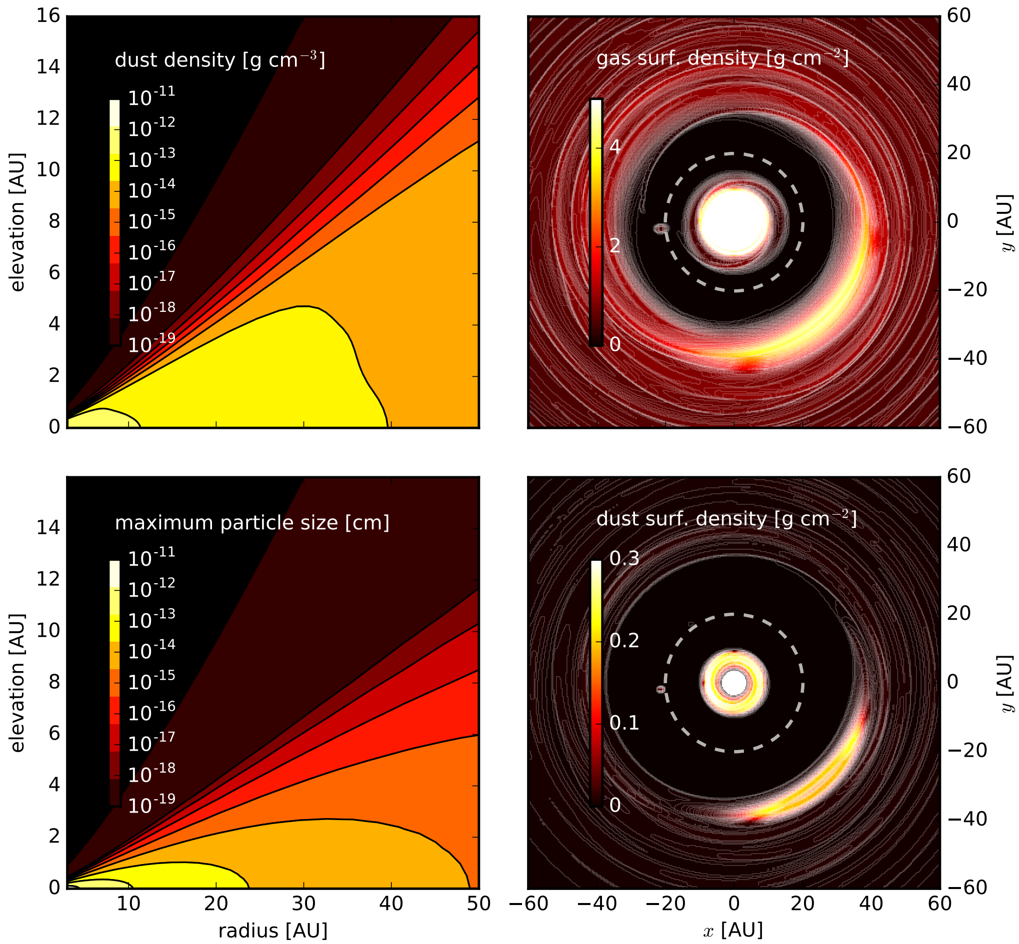


Figure 3: Proof-of-concept models for 2D dust evolution simulations. The panels to the left show the radial/vertical distribution of solids (top) and maximum particle sizes (bottom) where both coagulation and vertical transport processes are treated at each point of a 2D grid. The panels on the right 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.

**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.

**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.

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.

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.

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.

**XXX [Add more references, up to 10.] XXX**

# 2. Objectives and work programme

## 2.1 Anticipated total duration of the project

36 Months

## 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 effective can planetesimals be formed in pressure bumps?
- What properties of the pressure bumps are compatible with observational properties of protoplanetary 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.
- 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 extend of the pressure bump, the turbulence strengths or in particular with vortices in case the pressure bump becomes Rossby wave unstable?

**XXX continue here XXX**

## 2.3 Work programme including proposed research methods

### 2.3.1 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] (**?**). Further gradual improvements will include an $\alpha$-disk evolution (already implemented in the code) where the pressure bump forms due to parametrized variations in the $\alpha$-viscosity (**?**). This will allow us to look at time-dependent trapping processes, e.g. for pressure bumps with a finite life time. If necessary, the gas evolution 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 (**?**, and Klahr, Birnstiel, Lenz, in prep.). We will use Eq. 12 of **?**, which is a fit to detailed numerical results of **?** consistent with other works on planetesimal formation in the context of the streaming instability (e.g. **?**). 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 **?**. 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 **?**. 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. **??**). Using bumps of finite life time will allow us to investigate the efficiency of particle trapping in time-dependent pressure maxima, which is a significant improvement over previous works such as **?** and **?**. By linking this to existing millimeter wave radio-surveys (e.g. **?** and references therein as well as previous surveys such as **?**) we will be able to test which bump amplitudes, bump sizes, and life times are producing results consistent with (1) disk 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., **???**).

### 2.3.2 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] (**?**). 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

[1] http://birnstiel.github.io/two-pop-py/
[2] http://github.com/hannorein/rebound

to a super-particle approach, where one individual particle in the code represents a larger number of physical particles.

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 (**?**).

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. In this phase II of the research plan we will focus on the N-body treatment of the planetesimals and related science questions.

Based on 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 **?**, **?** 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:

On the one hand, the dust distribution (1) causes planetesimals to form based on the local metallicity and (2) causes planetesimals to grow via pebble accretion of particles of the right sizes. On the other hand, planetesimals reduce the dust mass by both of these effects. If this dust removal process is efficient no further planetesimals will be formed as the metallicity in the bump will be kept too low. Secondly, the reduction in dust mass might also reduce the particle sizes which further minimizes the amount of particles contributing to planetesimal formation. This letter 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.
- 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 lines of code and well reproduces the results of complicated coagulation codes. Combining these codes offers a student interesting quick 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.

### 2.3.3 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 (**??**), TW Hydrae (**??**), or HD 97048 (**?**), proving that the approach of the previous phases of this project is very relevant. However, other observations spectacularly show asymmetries **XXX REF XXX**.

- talk about vortex formation, dust-gas interaction

- talk about vortex-planet interaction
- talk about the **?** work and that we can start using it – or alternatively that we could with the experience from above include the planetesimals into the LA-COMPASS code.
- item talk about various possible mechanisms for forming a transition disk and that we can see how these scenarios affect the planet formation hot-spots

## 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[3] 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

# 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 €.

[3] 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.

#### 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

**XXX Text XXX**

#### 5.4.1.2 Collaborating researchers for this project outside of the Research Unit

**XXX Text XXX**

### 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