Project D1:
Transition disks and planetary systems

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Collaborations: B. Ercolano (USM)

Requested positions: 1 Postdoc

Abstract:
As described in the general introduction, transitional discs (TDs) presumably occur in the later phases of the evolution of protostellar discs around young stars and show a depletion of flux from the inner, central parts of the disc. One variety of such discs display a lack of radiation in the mm-wavelength regime which is interpreted as large inner holes in their dust distribution. Nevertheless they show significant gas accretion signatures coming from the central inner region. It has been suggested that for these type of TDs this inner cavity might be created by the presence of one or more planets that cleared out the inner disc region. In this project we shall follow this line of thought and will perform multi-dimensional hydrodynamic studies to clarify the dynamical impact of planets on TDs in order to prove (or disprove) the existence of planets in such discs. The studies will include gas dynamics, dust particles, embedded planets, radiation transport and irradiation from the central star.

1. State of the art and preliminary work

Observationally, transition discs are characterised by a lack of flux in the few μ-meter (near/mid IR) range as seen in the spectral energy distributions (SEDs) of young stars. This flux deficit is typically associated with 'missing' dust having temperatures of 200-1000 K (Calvet *et al.*, 2002; D'Alessio *et al.*, 2005) corresponding to the inner regions of accretion discs. Despite this lack of dust, there are nevertheless still signatures of gas accretion in several systems with large the inner (dust) holes that are a few tens of AU wide.

The origin of the inner disc clearing has been basically attributed to two different processes: either photoevaporation from inside out through high energy radiation from the central young protostar, or by embedded massive planets that carve deep gaps into the disc. While photevaporation is certainly at work in some systems (Type I TDs) it is believed that it can only operate for systems with a sufficiently low mass accretion rate below a few times $10^{-8} M_\odot/yr$ and is otherwise quenched by the accretion flow. At the same time the persistence of gas accretion within the inner (dust) holes is taken as an additional indication that other mechanisms should operate that create these gaps (Manara *et al.*, 2014). The most likely mechnism for this second class of TDs is related to the growth of planets in the discs, because planet formation essentially depletes the dust and reduces the gas density.

Consequently, it has been suggested early on that the presence of a massive (Jupiter-sized) planet might be responsible for the gap creation (Varnière *et al.*, 2006; Rice *et al.*, 2006) but at the same time it had been noticed that the gap created by a single embedded planet is way too narrow to be in agreement with the observations. Given the problems with a single planet and evaporation models it has been proposed that the main observational features can be created by the presence of a system (three to four) of massive planets. Following this line of thought, Zhu *et al.* (2011) and Dodson-Robinson and Salyk (2011) argue that transitional discs are in fact *Signposts of young multiplanet systems*. Despite this strong belief that planets play an important role in shaping transition discs, there is still a lack of theoretical modelling to be able to make detailed comparison with observations. The most advanced simulations are those of Zhu *et al.* (2011) who model a system of up to 4 massive planets embedded in a two-dimensional (2D) flat disc. Their studies suggest that the presence of the planets results in a strong depletion of the gas in the inner disc but there are several shortcomings. The simulations treat the disc in the isothermal approximation, they are only 2D and neglect the vertical structure, and no accretion luminosity of the planets was considered. Despite these limitations the most important constraints may be the omission of dust particles in the simulations, which is important as it is the dust emission that is actually observed.

In this project we plan to improve significantly on existing models for Type II TDs that contain a system of embedded planets. To this purpose we will perform a series of time-dependent multidimensional hydrodynamical simulations to study in detail the impact of a planetary system on the ambient disc. The new studies will first improve on the gas dynamics by adding radiative transport and including irradiation from the central star. Secondly, the motion of embedded dust particles will be followed which allows to study the dust and gas filtration process at the gap's outer edge. The results of the simulations will be used to calculate emission properties to be compared to the observations.

(text slightly extended from pre-proposal. more to be added).

1.1 Preliminary work

The PI of this project has ample experience in modelling accretion disks with embedded planets, starting from single embedded planets to a system of planets evolving into a resonant configuration. Initially two-dimensional (2D) studies in the isothermal approximation were performed and later full 3D studies including full radiative transfer. A summary of the topic of planet-disk interaction with references to several works of the PI is given in a review article in Annual Rev. of Astronomy & Astrophysics Kley and Nelson (2012). In the past years a study on the physics of transitional disk with one embedded massive planet has been conducted Müller and Kley (2013), and recently hydrodynamical simulations with embedded dust particles have been performed Picogna and Kley (2015); Stoll and Kley (2016). Here, we list some of the preliminary works relevant to this project.

1.1.1 On the accretion flow in Transitional Disks

In Müller and Kley (2013) two-dimensional hydrodynamical simulations using the grid-based code FARGO for disks with a single embedded planet were performed. In addition to isothermal models we added also radiative cooling from the disk surfaces, radiative diffusion in the disk midplane and stellar irradiation to the energy equation to have more realistic models. The mass flow rate into the gap region depends, for given disk thermodynamics, non-monotonically on the mass of the planet. Generally, more massive planets open wider gap and deeper gaps which would tend to reduce the mass accretion into the inner cavity. However, for larger mass planets the outer disk becomes eccentric and the mass flow rate is enhanced over the low mass cases. As a result, for the isothermal disks the mass flow is always comparable to the expected mass flow of unperturbed disks $\dot{M}_\mathrm{d}$, while for radiative disks the mass flow is very small for low mass planets ($\leq 4\,M_\mathrm{jup}$) and about 50 % of $\dot{M}_\mathrm{d}$ for larger planet masses. The mass accretion rate into the inner disk cavity and the gobal eccentricity of the disk is shown in in Fig. 1 for the $4\,M_\mathrm{jup}$ planet. For the radiative disks that critical planet mass for the disk to become eccentric is much larger that in the purely isothermal case. Overall we found that massive embedded planets can reduce the mass flow across the gap considerably, in the case of radiative disks, to values of about an order of magnitude smaller than the standard disk accretion rate.

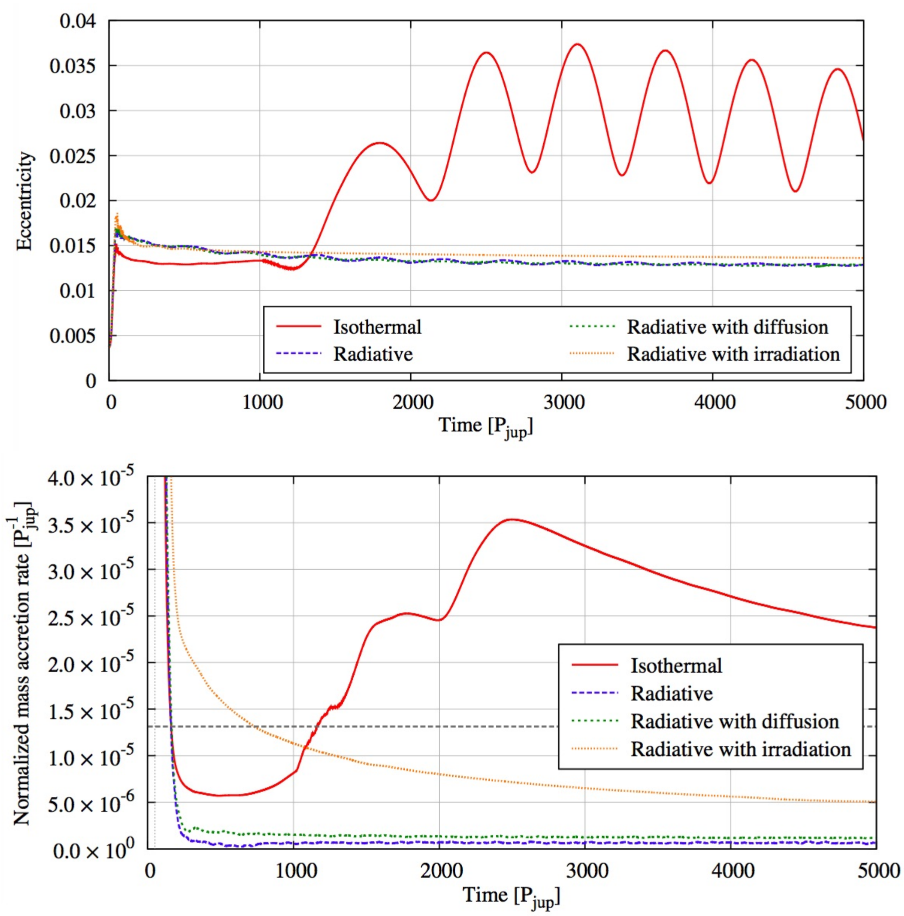

Figure 1: Time evolution of the the disk eccentricity (**top panel**) and the mass accretion rate (**bottom panel**) into the inner hole of the disk for a $4M_{Jup}$ planet in a transitional disk. Shown are curves for different thermodynamic treatments of the disk physics. Taken from: Müller and Kley (2013)

1.1.2 On the dust distribution in the disk around HL Tau

Upon publication of the spectacular image of the ring system in the HL Tau disk by the ALMA Partnership, we performed hydrodynamical simulations of the disk around HL Tau with embedded planets and dust particles. We followed the evolution of a population of dust particles treated as Lagrangian particles, in two-dimensional locally isothermal disks where two equal-mass planets are present. The planets were kept in fixed orbits and they did not accrete mass. The outer planet plays a major role in removing the dust particles in the co-orbital region of the inner planet and in forming a particle ring which have a steeper density gradient close to the gap edge respect to the single-planet scenario, promoting the development of vortices. The ring and gap width depend strongly on the planetary mass and particle stopping times. For the more massive cores the ring clumps in few points that are able to collect a high mass fraction. In summary we found that the features observed in the HL Tau system can be explained through the presence of two massive cores that shape the dust disk where the inner planet has a mass of the order of $0.07M_{Jup}$ and the outer ones of the order of $0.35M_{Jup}$. These values can be significantly lower if the disk mass turns out to be less than previously estimated. By decreasing the disk mass by a factor of 10, we obtain similar gap widths for planets with a mass of $10M_{Earth}$ and $20M_{Earth}$ for the inner and outer planets, respectively. Although the particle gaps are

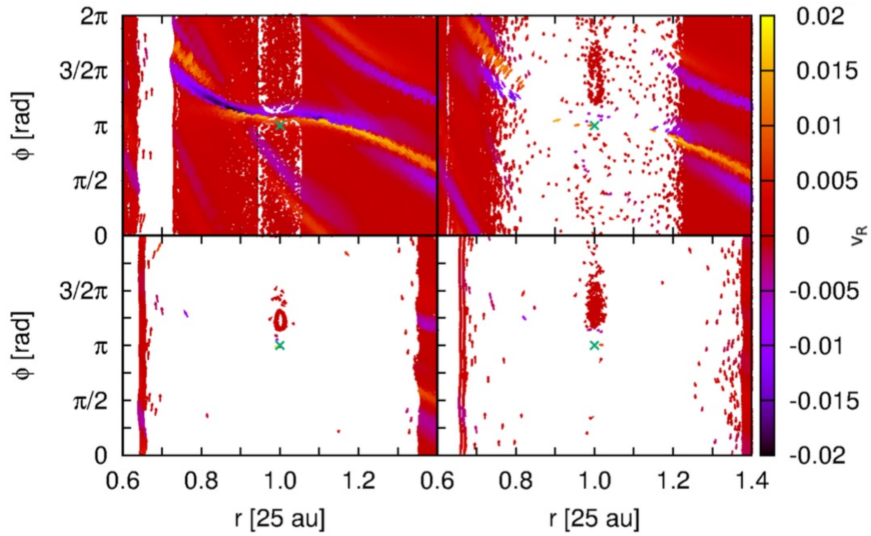

Figure 2: Particle distribution near the inner low mass planetary core location for mm- (top left), cm- (top right), dm- (bottom left), and m-sized (bottom right) particles at the end of the simulation. The velocity vectors of the particles with respect to the planet are shown and the colour scale shows the relative radial velocity. Taken from: Picogna and Kley (2015)

prominent, the expected gaseous gaps are barely visible. The final distribution of dust particles of different sizes is shown in Fig. 2, clearly the gap width depends on the size or better the dimensionless stopping time of the embedded particles, see eq. (3) below. For very small particles that couple well to the gas (top left panel) there is no strong gap visible while for larger, not so well coupled particles a strong gap will be opened in the dust distribution. Obviously this filtering effect will play a major role in determining the dust dustribution in transitional disks as well.

(more examples).

1.2 Project-related publications

A chronological list of selected relevant articles published or officially accepted by publication outlets with scientific quality assurance.

- Müller, T. W. A. and Kley, W. (2013) *Modelling accretion in transitional disks* Astronomy & Astrophysics, **572**, A61.
- Ataiee, S., **Dullemond**, C. P., **Kley**, W., Regály, Z. & Meheut, H. (2014) *Planet-vortex interaction: How a vortex can shepherd a planetary embryo*, Astronomy & Astrophysics, **572**, A61.
- **Kley**, W., Bitsch, B. & Klahr, H. (2009) *Planet migration in three-dimensional radiative discs*, Astronomy & Astrophysics, **506**, 971.
- **Kley**, W., Peitz, J. & Bryden, G. (2004) *Evolution of planetary systems in resonance*, Astronomy & Astrophysics, **414**, 735.
- Gorti, U., **Dullemond**, C. P. & Hollenbach, D. (2009) *Time Evolution of Viscous Circumstellar Disks due to Photoevaporation by Far-Ultraviolet, Extreme-Ultraviolet, and X-ray Radiation from the Central Star*, Astrophysical Journal, **705**, 1237.

2. Objectives and work programme

2.1 Anticipated total duration of the project

3 years.

2.2 Objectives

In this project we plan to improve significantly on existing models for Type II TDs that contain a system of embedded planets. To this purpose we will perform a series of time-dependent multidimensional hydrodynamical simulations to study in detail the impact of a planetary system on the ambient disc. The new studies will first improve on the gas dynamics by adding radiative transport and including irradiation from the central star. Secondly, the motion of embedded dust particles will be followed which allows to study the dust and gas filtration process at the gap's outer edge. The results of the simulations will be used to calculate emission properties to be compared to the observations.

2.3 Work programme including proposed research methods

The hydrodynamical simulations will make use of the PLUTO-code. Using the spatial distribution of the dust and gas we will use the radiative transport code RADMC-3D for making observational predictions from our models. The project will contain the following steps: :

1) To connect to existing simulations of (Zhu *et al.*, 2011) and our own (Müller and Kley, 2013) the first hydrodynamical models will be performed for flat 2D locally isothermal discs that contain several planets. In a parameter study the planetary masses will be varied systematically, and the resulting equilibrium density configurations will be analysed. The 2D isothermal models will be extended by radiative cooling and transport similar to Müller and Kley (2012). For these models first emission maps will be calculated using the RADMC-3D code.
2) Dust particles will then be added to these models whose motion is determined by the particle size and the gas density of the disc. In parameter studies the disc mass, the planet mass and the particle radii will be varied in order to determine the dust depletion factor within the central cavity relative to the gas accretion rate as a function of these parameter. For this work we shall be using the methods developed in Picogna and Kley (2015)
3) From the 2D-runs the most promising parameter sets will be selected to perform full 3D time dependent hydrodynamical simulations using the PLUTO-code. Using the resulting gas and dust spatial density distribution the RADMC-3D code will be applied for making observational predictions from our models. This can be used for both, continuum and line emission.
4) In the last part we will make the models more realistic and use an improved equation of state and internal (viscosity) as well as external (stellar irradiation) heat sources in the simulations. Accretional heating from the mass accretion of planet will be taken into account as well.

2.3.1 Tools for the proposed project

FARGO-code **(fargo characteristics)**

PLUTO-code **(pluto characteristics)**

2.3.2 Work plan

The work plan consists of several sub-projects that follow the general outline of the overall project goals. It consists of multi-dimensional hydrodynamical simulations with increasing complexity. It is conveniently divided into the following Tasks:

Task 1 *2D hydrodynamical simulations of protoplanetary disks with multiple embedded planets*
In this first part of the project we plan to perform 2D simulations of flat accretion disks with multiple embedded planets. To become familiarized with the topic and connect to the existing simulations by Zhu *et al.* (2011) in the first stage the simulations will be in the locally isothermal approximation. These simulations will be performed simultaneousy with the FARGO-code and with our new GPU-PLUTO code for selected parameter sets similar to those chosen in Zhu *et al.* (2011). For comparison to our own work of (Müller and Kley, 2013) we will run a few single planet calculations for planets of varying mass in the isothermal models. Having verified the accuracy of our treatment, in particular ensure agreement between the two codes used, we shall extend the simulations with important physics. One strong handicap of many existing single- multi-planet simulations is the assumption of an isothermal gas. Due to the inability of the gas to cool when beeing transfered into the inner hole of the disk the gas flow will typically be overestimated significantly as shown in our direct comparison simulations (Müller and Kley, 2013). We will add internal and external heating processes by including viscous effects and irradiation by the central star as introduced in our previous works Kley and Crida (2008); Müller and Kley (2012, 2013). Cooling from the disk surfaces will be calculated by suitable averaging processes from the temperature of the disk. Some of this physics is presently been introduced into the GPU-version of the PLUTO code but will need further testing. For these fully radiative simulations the planet masses will be varied and they will be able to accrete material from the disk environment. Initially the planets are held fixed on their orbits but will then be allowed to move according to the forces acting on them by the star, the other planets and the disk material. The disk self-gravity will most likely not be important by its influence on the planetary dynamics will be checked. For the obtained density structures we will calculate synthetic images and spectra using our RADMC-3D code. For which we will extend our 2D simulation by a vertical structure in hydrostatic equilibrium.

Task 2 *Dust evolution in 2D dimensional disk simulations with embedded protoplanets*
As outlined in the preliminary work, the motion of dust particles in disks is strongly influenced by the presence of embedded planets in the disk. A planet creates gap in the disk where the density and hence pressure is lowered with respect to the ambient disk. At the gap edges there are maxima in the pressure distribution of the disk created. The altered radial pressure gradient has an impact on the motion of the gas particles in the disk as they feel the changing pressure gradient. At the outer gap edge the pressure gradient is positive which leads to an super-Keplerian azimuthal flow velocity while beyond the pressure maximum the gradient is negative again. On the other hand unperturbed dust particles do not feel the pressure gradient but move with speeds equal to the Keplerian orbital angular velocity. This difference in velocities of the gas and the particles leads to drag forces between them and to a collection of dust particles near the outer edge (pressure maximum) of the gap. This effect is illustrated for two embedded planets in Fig. 2 for the disk around HL Tau. The inner edge of a transition disk is in structure very simular to the outer edge of a planetary gap in fact identical if the gap is created by a few planets. Hence, dust particles will be filtered there according to their sizes (see Fig. 2).

In this second task of the project the motion of embedded dust particles will be followed simultaneously with the hydrodynamical evolution of the disk. This has not been done yet in the context of transitional disks. Individual Langragian particles of different size will be added to the hydrodynamics of the disk, and they will move under the influence of the gravitating objects (star and planets) and experience the gas drag. The accelaration acting on a dust particle due to these forces is then given by

$$\frac{d\vec{x}_p}{dt} = \vec{u}_p \qquad\qquad \frac{d\vec{u}_p}{dt} = \vec{f} - \frac{\vec{u} - \vec{u}_p}{t_s}\,, \tag{1}$$

where $\vec{f}$ contains the external forces acting on the particle (gravitational atraction due to the star and the planets), $\vec{u}$ denotes the velocity of the gas and $\vec{u}_p$ of a dust particle, and t_s is the so called stopping time. Our focus will be on particles in the Epstein-regime for which the mean free path of the gas molecules is typically greater than the particle cross section and t_s is given by (Epstein, 1924)

$$t_s = \frac{1}{\sqrt{8/\pi}} \frac{r_p \rho_p}{\rho_g c_s} \,. \tag{2}$$

Here, r_p is particle radius, ρ_p the particle bulk density, ρ_g the gas density, and c_s is the sound speed. In case other drag forces (Stokes-regime) become necessary it is relatively straight forward to implement those for example by the methods suggested in Haghighipour and Boss (2003). As expected, the drag force depends on the particle and gas properties and to estimate its importance it is convenient to define the dimensionless stopping time by

$$\tau_s = t_s \Omega_K \tag{3}$$

where Ω_K is the Keplerian angular frequency. From eq. (1) it is clear that particles small dimensionless stopping times will be well coupled to the gas such that $\vec{u}_p \approx \vec{u}$, for very large τ_s (for example bigger particles with larger r_p) will be decoupled and do not fell the gas. Hence, the most important parameters are those for which $\tau_s \approx 1$. We have implemented the time integration of eqs. (1) into the 2D FARGO-code (Picogna and Kley, 2015) and into the 3D-PLUTO code (Stoll and Kley, 2016) using the semi-implicit method of Bai and Stone (2010) using eq. (1) in cylindrical coordinates. After having performed the necessary test calculations to verify the accuracy of the integrator detailed parameter studies will be performed in order to calculate the efficiency of dust filtering at the inner edge of the disk. This will allow us to determine the dust depletion factor in the inner hole as a function of the planet masses, dust and disk properties.

Task 3 *Full three dimensional disk simulations with embedded protoplanets*
In this part of the project we will extend the previous 2D simulations to full 3D. From our own first experience in peforming simulations for transitional disks (Müller and Kley, 2013) in only 2D we know that many dynamical timescales of the disk will have to be calculated. Hence, we expect full 3D simulation to extremely costly concerning CPU-resources. Hence, we plan to use new, recently developped codes that run very efficiently on GPU-processors. In particular, for these type of simulations we plan to utilize our newly developed 3D GPU-PLUTO code (Thun *et al.*, 2016) to speed up the simulations. Of course, comparison test simulation using the standard MPI-version of PLUTO or the new FARGO3D code for GPUs, as described in Benítez-Llambay and Masset (2016) will be performed. For more details on such codes see Sect. 2.3.1.

Despite the possible improvements in computational speed full 3D simulations will be very demanding in computational resources. To alleviate this problem at least partly we plan to run dedicated models for selected parameter sets that we expect from the 2D simulations of the previous tasks to be the most promising. In a first step we plan to compare a few selected examples for isothermal setups and calculate the differences between 2D and 3D results. From recent studies of a pair of giant embedded planets that capture each other in mean motion resonance there should not be such a strng difference between isothermal 2D and 3D results (André and Papaloizou, 2016) if both planets are located in the midplane of the disk. We will check this for a few selected cases using the coplanar setup. Then we plan to extend this study to non-coplanar planetary orbits and and investigate the influence of small inclinations between the planets and the disk. For this part of the project we plan intensive collaboration with project D2.

After successful isothermal simulations we will include radiative transfer and viscous heating in full 3D. Here, we plan rely initially on our implementation of radiative transfer and stellar irradiation for the PLUTO code (Kolb *et al.*, 2013). Here, the radiative transport is using the flux-limited diffusion approximation while stellar irradiation is modelled directly using a ray-tracing method. As indicated already in Müller and Kley (2013) we expect significant differences between the isothermal and fully radiative cases, as indicated in Fig. 1 for the 2D case and with single embedded planet.

Task 4 *Improved physics*
(This has probably been dealt with already in the other tasks.)

2.3.3 Links to the other Forschergruppe projects and international collaborators

The team (Kley, Dullemond, Ercolano) have all the necessary expertise to carry out the hydrodynamical numerical modeling and calculating observational implications to compare to existing observations.

(Is the following still o.k. here: In addition collaboration with the groups of Th. Henning (MPIA), E. van Dishoeck (MPE/Leiden), M. Benisty (Grenoble/Santiago) and C. Dominik (Amsterdam) is envisioned for the comparison to observational data with ALMA and SPHERE.)

2.4 Data handling

The model data we produce will be made immediately available online, once the corresponding paper is accepted.

2.5 Other information

2.6 Information on scientific and financial involvement of international cooperation partners

For scientific involvement, see the list of external collaborators.
[CHECK]

3. Bibliography

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4. Requested modules/funds

4.1 Basic Module

4.1.1 Funding for Staff

We request 1 Postdoc E13 position for three years, to be based at the Institute of Astronomy and Astrophysics at the University of Tübingen.

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 high end workstation including a modern GPU-card. This is beyond the standard base equipment (*Grundausstattung*). We therefore request one workstation-grade desktop computer for 4000 Euro.

4.1.2.2 Travel Expenses

Participation at at least one conference per year, or similar is anticipated for the postdoc. In addition to travel funds for conferences for the PIs, regular mutual working visits at Heidelberg/Tübingen/München are planned.

	Year 1	Year 2	Year 3	Sum
Conferences Postdoc	1500	1500	1500	4500
Conferences PIs	2000	2000	2000	6000
Working visits Heidelberg/TübingenMünchen	3000	3000	3000	9000
	6500	6500	6500	**19500**

4.1.2.3 Visiting Researchers (excluding Mercator Fellows)

To be added.

	Visit 1	Visit 2	Sum
Prof. Andrea Mignone (University Torino, Italy)	1000	1000	2000
	4000	4000	**8000**

4.1.2.4 Other Costs

4.1.2.5 Project-related publication expenses

We will publish in the **free European Journals** Astronomy & Astrophysics and Monthly Notices of the Royal Ast. Society.

5. Project requirements

5.1 Employment status information

Kley, Wilhelm: Prof. Dr., full Professor with tenure at the University of Tübingen, Institute for Astronomy & Astrophysics

Dullemond, Cornelis P.: Prof. Dr., full Professor with tenure at the University of Heidelberg, Institute for Theoretical Astrophysics

5.2 First-time proposal data

5.3 Composition of the project group

The project is a joint activity of the Computational Astrophysics group (CPT) at the Institute of Astronomy and Astrophysics of the University of Tübingen (IAAT), and the Institute for Theoretical Astrophysics (ITA) which is part of the Zentrum für Astronomie (ZAH) at the University of Heidelberg. The PIs Kley and Dullemond were both members of the past DFG research group *The Formation of Planets: The Critical First Growth Phase* (FOR 759) and plan to join their expertise and collaborate within this project. Within their groups at the IAAT and ITA the following scientists work presently in a research field related to this project:

- Kley, Wilhelm; Prof. Dr. — *Professor, IAAT (CPT)*
- Dullemond, Cornelis P., Prof. Dr. — *Professor, ITA (ZAH)*
- Kuiper, Rolf, Dr. — *Emmy Noether Group Leader, IAAT (CPT, DFG)*
- Schäfer, Christoph; Dr. — *Research Assistant, IAAT (CPT)*
- Thun, Daniel, Dipl.Phys. — *PhD student, IAAT (CPT, DFG)*

Emmy Noether Group Leader Rolf Kuiper has recently extended his activities into the field of planet formation and is an an expert in computational astrophysics. Research assistant Christoph Schäfer has ample experience in the field of planet formation and with GPU-computing. They both can give helpful advice to the Postdoc. The PhD student Daniel Thun has developed the GPU version of the *PLUTO*-code and can give helpful advice on related questions.

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

(point out the close collaboration between projects D1 and D2. Complementary approaches, similar methods, frequent excanges, etc...)

5.4.1.2 Collaborating researchers for this project outside of the Research Unit

The following external researchers will be involved to some degree in the work on this project:

- Bitsch, Bertram — *Lund University (S)*
- Regaly, Zsolt — *Konkoly Observatory, Budapest (HU)*

Former PhD student Bertram Bitsch is now a postdoctoral researcher in Lund (Sweden). His expertise in planet-disk simulations and torque-formulae for migration will be helpful for the project. With Zsolt Regaly from Budapest both PIs have long standing successful collaborations in the proposed research field in all relevant aspects: planet formation, celestial mechanics and computational astrophysics. We plan to continue the collaboration with them in this project.

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

The PIs have worked with the following scientists in research fields related to planet formation. Only more senior scientist and postdocs are listed, no PhD students.

Baruteau, C. (University of Toulouse, F); Bitsch, Bertram (Lund Observatory, S); Blum, Jürgen; Schräpler, Rainer (both Universität Braunschweig); Dullemond, Cornelis, P. (Universität Heidelberg); Haghighipour, Nader (Institute for Astronomy, University of Hawaii, USA); Masset, Frederic (University of Mexico); Meru, Farzana; Papaloizou, J.C.P. (both University of Cambridge, GB); Mignone, Andrea (University of Torino, I); Nelson, Richard and Paardekooper, S.J. (University of London, Queen Mary, GB); Regaly, Zsolt (University of Budapest, H); Rein, Hanno (University of Toronto, Canada); Vorobyov, Eduard (University of Vienna, A);

S. Andrews (CfA, Harvard), E. van Dishoeck (MPE Garching, Uni Leiden), C. Dominik (UvA, Amsterdam), A. Natta (DIAS, Dublin), L. Testi (ESO, Garching), J. Carpenter (Caltech, Pasadena), C. Chandler (NRAO, Socorro), A. Isella (Rice Uni, Houston), L. Ricci (Caltech, Pasadena), N. Calvet (Uni Michigan), S. Corder (ALMA), J. Greaves (Uni St. Andrews), N. Turner (JPL, Pasadena), A. Uribe (Coll. Charlston), Z. Regaly (Konkoly Obs, Budapest), A. Juhasz (Cambridge), R. Klessen (Uni-Heidelberg), R. Kuiper (Uni Tübingen), C. Brinch (University of Copenhagen), M. Benisty (Uni Grenoble), P. Pinilla (Tucson), C. Mordasini (Uni Bern), G. Guidi (ESO), M. Tazzari (ESO), L. Perez (MPIfR, Bonn), H. Linz (MPIA), A. Sargent (Caltech, Pasadena), L. Mundy (University of Maryland), S. Storm (University of Maryland), J. Lazio (JPL, Caltech), W. Kwon(Korea Astronomy and Space Science Institute), T. Muto (Kogakuin University), M. Momose(Ibaraki University), T. Tsukagoshi (Ibaraki University), L. Klarmann (Uni Amsterdam), H. Klahr (MPIA, Heidelberg), S. Ataiee (Uni Bern), M. Fukagawa (NAOJ Japan), H. Shibai (Osaka University), T. Hanawa (Chiba University), K. Murakawa (Osaka Sangyo University), J. Ramsey (Uni Kopenhagen), J. Drazkowska (Uni Zürich)

5.5 Scientific equipment

The project requires, at least for the full hydrodynamical simulations, a considerable amount of CPU-time. For this we rely on own as well as outside resources. For testing purpose computing time will be available on local PC clusters (institute and university clusters). Here we have dedicated GPU-systems available as well as smaller clusters.

We have special access to computing resources supplied within the State of Baden-Württemberg (Baden-Württemberg High Performance Computing - Coordinated Compute Cluster Competence Centers: bwHPC-c5). A part of this initiative is the new BinAC-system[1] that has just gone online at the University of Tübingen and is dedicated to Astrophysics and Computer Science only. BinAC offers over 236 CPU nodes with dual Intel Xeon E5-2630v4 each. Moreover (and especially suited for our GPU-*PLUTO*-code) the cluster also offers 60 GPU nodes with dual Nvidia Tesla K80 (with two GK210 GPU chips each). Additional resources are available with bwHPC-c5 at the ForHLR-cluster at the Steinbuch Centre for Computing (SCC) in Karlsruhe. If further resources will be required we will apply for additional computer time at the high performance computing center HLRS, located in Stuttgart, and at other centers in Germany.

5.6 Additional information

[Text]

[1] see `http://www.bwhpc-c5.de/wiki/index.php/Category:BwForCluster_BinAC` for a detailed description of the hardware.