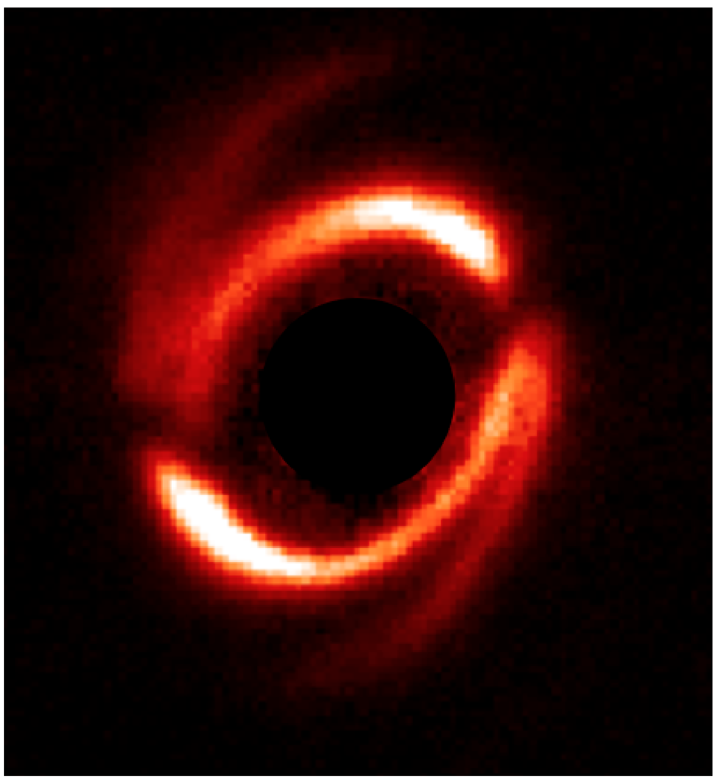
Planet Formation Witnesses and Probes: Transition Discs

Proposal for funding a DFG Research Unit



Speaker: Barbara Ercolano

Co-speaker: Cornelis Dullemond

Cover image: The Transition Disk HD 100453 as seen with the VLT-SPHERE instrument in scattered polarized light. From: Benisty et al. 2017, A&A in press.

NOTE: We have to ask permission from the main author (Myriam Benisty) and the SPHERE consortium to use this image. We can also use another image, or use a theoretical model.

1. Participating institutes and principle investigators

- **Ludwig Maximilians University Munich (LMU):**
  - University Observatory
    (Prof. Dr. Barbara Ercolano, Prof. Dr. Thomas Preibisch, Dr. Tilman Birnstiel)
- **European Southern Observatory, Garching:**
  - Star and planet formation group
    (Dr. Leonardo Testi)
- **Max-Planck-Institute for Extraterrestrial Physics, Garching:**
  - Centre for Astrochemical Studies
    (Prof. Dr. Paola Caselli)
- **Ruprecht-Karls-University Heidelberg:**
  - Institute for Theoretical Astrophysics (ITA)
    (Prof. Dr. Cornelis P. Dullemond)
- **University of Tübingen:**
  - Institute for Astronomy & Astrophysics
    (Prof. Dr. Wilhelm Kley)

Speaker:
Prof. Dr. Barbara Ercolano — Tel.: 089-2180-6974
University Observatory
Ludwig Maximilians University Munich — e-mail ercolano@usm.lmu.de
Scheinerstr 1, D-81679 München

Co-speaker:
Prof. Dr. Cornelis P. Dullemond — Tel.: 06221-544815
Institute for Theoretical Astrophysics
Heidelberg University — e-mail dullemond@uni-heidelberg.de
Albert Ueberle Str. 2, D-69120 Heidelberg

2. Summary

Recent surveys have shown an overwhelming diversity of extrasolar planetary systems, prompting the question of how did they form, and whether some may end up looking like our own and being able to sustain life. Hints to answer such fundamental questions may be hidden in the many trends that are slowly emerging from the data. An example are the deserts and peaks in the distribution of giant exoplanets, with clear implications for habitability of systems, given the role played by giants on the delivery of volatiles to terrestrial planets (e.g. Quintana & Lissauer 2014).

The environment in which planets form plays a major role in understanding both exoplanet diversity and the emerging trends. Planets are born out of the dust and gas left over whenever a new star forms: the protoplanetary disc. The initial conditions for planet formation are thus determined by the protoplanetary discs, which evolve and disperse as they give birth to planets. Interestingly, the timescales of disc dispersal are comparable to those of planet formation, suggesting that the dispersal mechanism dominates disc evolution right at the time at which planets form. Conversely, the planet formation process also strongly affects the disc, making the combined problem of planet formation and disc evolution a strongly coupled and complex problem.

Discs on the verge of dispersal, so-called “Transition Discs” (TDs), are thus particularly important witnesses of the planet formation process, and they can be used as probes of the different mechanisms at play at this crucial time of disc evolution. Latest research has shown, however, that TDs, which are usually identified as discs showing evidence of an (at least partially) evacuated inner dust hole, are in reality a diverse class of objects. Some TDs have relatively small dust holes (a few AUs) and are weakly accreting, if at all. On the other hand an apparently distinct population of TDs show evidence for much larger inner dust cavities (several to many tens of AU) and vigorous accretion, signifying that a large amount of gas is present inside the dust cavity. Different physical processes may be at play for the formation of different TD types (e.g. photoevaporation, MHD processes, dust evolution, planet-disc interactions), each being a piece of the complex planet formation puzzle.

Until recently, observations of protoplanetary discs provided very few constraints on our understanding of disc evolution and planet formation. That was in part due to the lack of spatial resolution of telescope facilities at infrared and (sub-)millimetre wavelengths, but also in part because protoplanetary discs tend to be opaque, and therefore much of the planet formation process is hidden from view. Both these obstacles impede an unobstructed view of the physical processes happening inside these planetary nurseries. Both problems may now start to be overcome with the enormous recent advances in the observational facilities. At near infrared wavelengths and at millimetre wavelengths we now start to obtain extraordinarily detailed images of these discs. They turn out to feature complex (often non-axisymmetric) structures that challenge our theoretical understanding of these discs. In particular, many TDs show spectacular structures including lopsided blobs, rings, spirals etc. It is suspected that some of these complex structures may be caused by newly formed giant planets that gravitationally perturb the disc, but exciting new alternative explanations, which not always involve planets are also emerging.

In our proposed Research Unit we aim at studying various aspects of TDs, leading to a better understanding of the different formation mechanisms of this very diverse class of objects. TDs are only now really becoming spatially resolvable thanks to facilities like ALMA and VLT-SPHERE, making their study a timely and urgent task. Only understanding the disc evolution and the planet-disc interactions allow the large body of existing and planned observations to be exploited to answer more complex questions like the formation of planetary systems capable to host life.

The answers to the many unsolved questions require a focussed effort from several com-

munities to devise a multi-pronged strategy to approach this complex problem. Specifically, multiwavelength observations of discs at different stages of evolution together with exoplanet and disc statistics should be used to constrain a concerted theoretical modelling effort including the hydrodynamics of the dust and gas component of discs, with and without planets, joint to chemical and radiative transfer calculations, particularly of the surface layers and winds of discs in (or just before) the transition phase. This is the motivation for the proposed Research Unit.

3. Introduction and motivation

The question of whether the Earth may be a unique and special place for life in our Universe has been the prime motivation for exoplanet finding missions and continues to be the driving force behind many observational campaigns and theoretical investigations in the field. While this question may have partially been answered by the recent exoplanet surveys, which have shown that, statistically speaking, most stars in the Milky Way have planetary companions (Cassan et al. 2012), other surveys have also highlighted the diversity of exoplanetary systems (Mullally et al. 2015). The question however remains as to which initial conditions may lead to the formation of planets. To answer this question many more aspects of the planet formation process and of their subsequent evolution must be understood.

Planets form from the dust and gas contained in the circumstellar discs surrounding nearly all young low- to intermediate-mass stars. These planet-forming discs are a by-product of the star-formation process, meaning that all stars have the potential to host a planetary system. Circumstellar discs are observed to evolve and finally disperse over a timescale of a few Myr, which is comparable to the timescales for planet formation by the core accretion process and to migration timescales for giant planets (see Armitage 2011 for a review). This implies that the processes driving the evolution and dispersal of discs play a crucial role in shaping new planetary systems and likely contribute to the observed variety of exo-planets (see e.g. Alexander & Pascucci 2012; Ercolano & Rosotti 2015).

For the largest part of their lives, the evolution of the surface density of discs seems to be well described by simple viscous theory (e.g. Hartmann et al. 1998; Lynden-Bell & Pringle 1974). This predicts a slow, homogeneous dispersal of the disc. Observations, however, show that the dispersal is not a continuous process: after having evolved viscously for a few million years, discs regularly seem to disappear abruptly (e.g. Kenyon & Hartmann, 1995; Luhman et al. 2010). Indeed studies have shown that the dispersal timescales are about 10 times faster than the global disc lifetimes, and that discs mostly disperse from the inside-out (e.g. Ercolano, Clarke & Hall 2011; Koepferl, Ercolano et al. 2013). 'Transition Discs' (TDs), i.e. discs that have an evacuated inner cavity in dust (or at least an inner region which is severely depleted in optical depth), may represent discs caught on the last gasps of their lives and may thus provide key insights on the mechanism responsible for their evolution.

It is however becoming clear that transition discs, which are identified observationally as having reduced near- to mid-infrared emission, are in reality a diverse class of objects. Some of them may not actually be short-lived objects caught in the act of dispersing their discs, but rather produced by a different rarer and longer lived phenomenon (see e.g Owen 2015, Dong & Dawson, 2016). **It is of prime importance to understand the physical processes leading to the formation of gaps and holes in planet forming discs, if these are to be used as probes of disc dispersal and/or planet formation. This is the overarching goal of this Research Unit.**

A number of theoretical models have been proposed for the origin of transition discs, some of which are true disc-dispersal processes (e.g. Photoevaporation: Clarke, Gendrin & Sotomayor 2001; MRI-driven winds: Suzuki & Inutzuka 2009; MHD winds: Bai 2016), while others rather lead to dust-(and sometimes also gas)-depleted regions yielding the observed infrared dip (e.g. Planet-disc interactions: Calvet et al. 2005; dust grain growth: Dullemond & Dominik 2005; binary stars interactions: Marsh & Mahoney 1992), without necessarily leading to the removal of the disc.

Photoevaporation by energetic radiation from the central star is currently accepted as one of the main players in the late evolution of discs and has seen several dedicated theoretical efforts (e.g. Clarke et al. 2001, Alexander et al. 2006, Ercolano et al. 2008a, 2009, Owen, Ercolano & Clarke 2010, 2011a, 2012, Gorti, et al. 2009a, 2009b, 2015). Photoevaporation is successful in reproducing the observed dispersal timescales, the inside-out mode of disc dispersal, and can reproduce a subset ($\sim$50%) of the TD demographics around T-Tauri stars.

However, disc dispersal by photoevaporation, while certainly an important piece of the puzzle, does not tell the whole story behind the formation of TDs. It has recently become apparent that TDs are a very diverse class of objects. **Amongst the TD zoology, at least two separate classes seem to have emerged, which we will refer to in this proposal as Type 1 and Type 2 TDs. Type 1 TDs have small (a few AU) inner dust holes and show weak or no accretion of gas onto the central star. Conversely, Type 2 TDs have much larger inner dust cavities (tens of AU) and show evidence of vigorous accretion ($\sim$10^{-8} M$_\odot$/yr), with rates not too dissimilar from those measured on primordial discs (e.g. Manara et al. 2014). Type 2 TDs also tend to have high mm flux levels, meaning that they still contain large amounts of material in their outer regions.** Owen & Clarke (2012) showed that it is statistically unlikely that these two groups of objects may be drawn from the same underlying population. When talking about TD demographics it is then important to draw the distinction between the two types, as the dominant formation mechanism is probably different.

Figure 1 shows a collection of known accretion rates versus inner hole radii for known TDs (Ercolano & Pascucci, 2017, in preparation), represented by circles. These are compared to photoevaporation model tracks from Owen et al. (2011), grey squares, and the photoevaporation models plus giant planet of Rosotti et al. (2013, 2015), grey lines. If stars of spectral type G or earlier (distinguishable by a light blue circle in the figure) are excluded, about half of the global TD population consists of Type 1 discs. The formation of Type 1 TDs is generally well reproduced by photoevaporation models (e.g. Owen et al. 2010, 2011a). The large accretion rates and large hole radii of Type 2 TDs, on the other hand, are problematic for all photoevaporation models (e.g. Rosotti, Ercolano et al. 2013, 2015) or grain growth models (Birnstiel, Andrews & Ercolano 2012) to date, and the classical explanation is that these objects may have instead been carved by dynamical interactions with forming giant planets (e.g. Zhu et al. 2011). However, since the current models based on the classic planet scenario also generally fail to reproduce the Type 2 TD observations and their demographics (e.g. see Dong & Dawson 2016), a number of alternatives have recently been proposed which include magnetohydrodynamics effects (e.g. Wang & Goodman, 2016), dust evolution (Pinilla et al. 2016) and inner disc asymmetries (Montesino et al 2016).

ALMA allows to measure the bulk of the molecular gas *directly*, showing than many Type 2 TDs have residual gas inside the dust cavities (van der Marel et al., 2016), in agreement with the planet scenario (but see also Wang & Goodman 2016). Furthermore, spatially resolved observations of type 2 TDs have shown many bizarre features that are not generally seen in primordial disks. For instance, they often display a huge dust ring (e.g. Casassus et al. 2013) which is sometimes strongly lopsided (e.g. van der Marel et al. 2013). The currently favored interpretation is that we see a key process of planet formation in action here: the mechanism of dust trapping in pressure maxima. Another spectacular kind of features often seen in TDs is spiral waves similar to those seen in galaxies (e.g. Muto et al. 2012, Benisty et al. 2015, Wagner et al. 2015). Their origin is currently not understood, and trying to understand their physics may teach us about important processes taking place in these

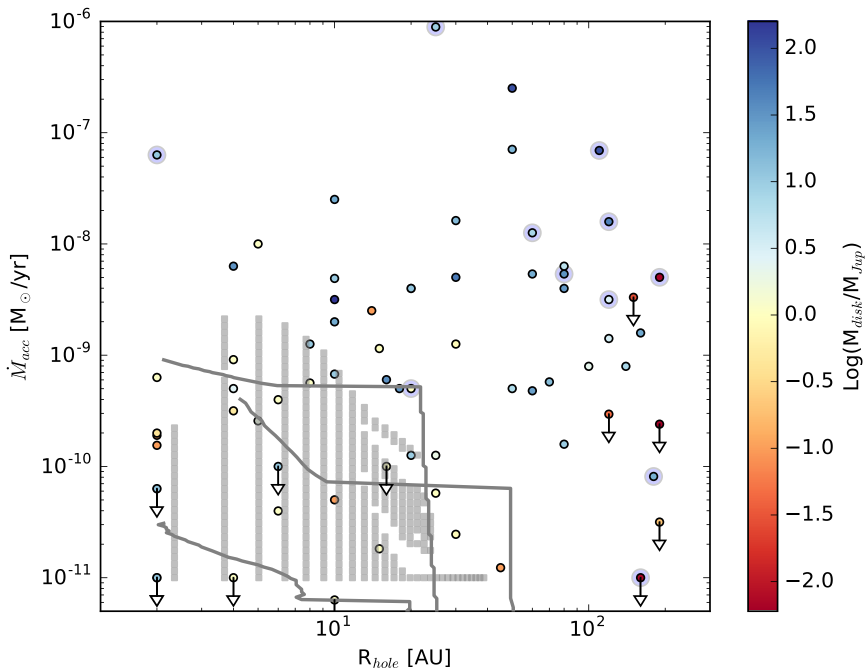


Figure 1: Mass accretion rate versus hole size for known transition discs (Ercolano & Pascucci 2017, in preparation). Circles are for observed star-disk systems. The color-coding shows total disk masses estimated from SED fitting. Sources surrounded by a light blue circle have spectral types G and earlier. Grey squares are snapshots of EUV- plus X-ray-driven photoevaporating discs from Owen et al. (2011) while grey lines are evolutionary tracks for the same photoevaporating discs with an embedded giant planet (Rosotti et al. 2013).

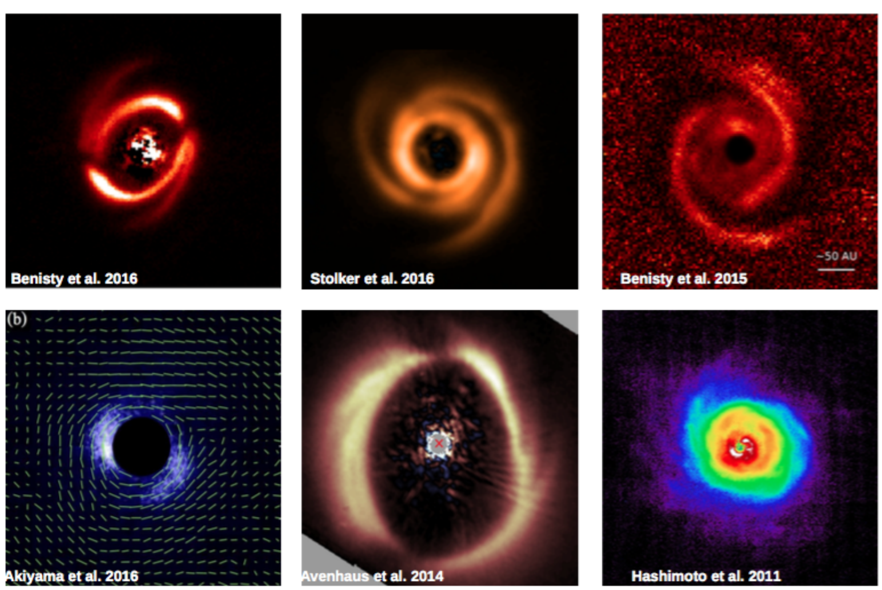


Figure 2: A gallery of scattered light images of Type 2 Transition Disks. **From left to right, top to bottom:** HD 100453, HD 135344b, MWC 758, LkHα 330, HD 142527 and AB Aurigae.

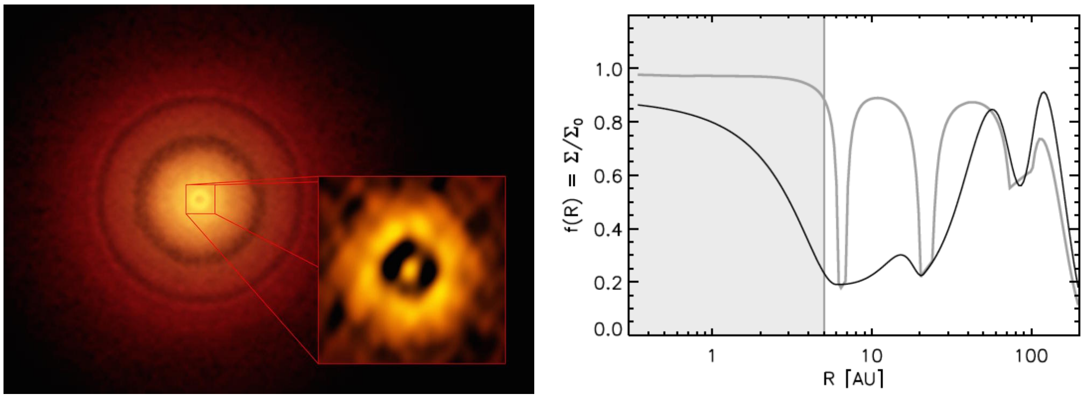


Figure 3: **Left:** ALMA image of the disk around the young, Sun-like star TW Hydrae. The inset image (upper right) zooms in on the gap at 1 AU . **Right:** Comparison between the derived radial surface density depletion factor (f(R), black curve) from van Boekel et al. (2016) and an implementation of the model of Duffell (2015) with three planets, approximately matching the depth of the gaps (grey curve). The innermost disk regions that are not well probed by the observations are masked.

discs. One interesting new scenario, for example, was proposed to explain the bright ring of scattered light of HD 142527 which has two dark spots on roughly opposite sides (see Fig. 2). Marino et al. (2015) suggest that the shadows cast by an inclined small inner disk could explain the location of the spots, implying that HD 142527 is an "inclined disc inside a disk". In that case, Montesinos et al. (2016) claim that two shadows on opposite sides of the bright rim may cause a brief pressure loss and be at the origin of the m = 2 spiral waves. If confirmed this scenario opens a pandora of new physical questions as to how could the inner disc have a different rotation axis as the outer one?

3.1 What can we learn about Planet Formation from TDs?

Both types of TDs can provide complementary information about the planet formation process, if the observations can be interpreted within a comprehensive theoretical framework. Type 1's can inform us over the disc dispersal mechanism, which influences the physical conditions in the disc at the time of planet formation and migration. Type 2 TDs, if indeed formed by dynamical interactions with giant planets are direct witness of the planet formation process. Importantly, all disc-destruction mechanisms essentially 'open up' the disc, so that we can peek inside to see its inner workings, and see processes of planet formation in action. TDs therefore have the unique potential of unveiling key aspects of the planet formation process.

As mentioned above, as well as disc morphology, the interplay between disc evolution and dispersal and the planet formation process, of which both types of TDs are a by-product, is apparent on many other levels. For example the lifetimes of protoplanetary discs (a few Myrs) are comparable to the timescales for planet formation via the core accretion model. This highlights the relevance of studying discs at the end of their lives (i.e. TDs), and highlights the importance of the disc dispersal mechanism (e.g. photoevaporation) which sets the physical conditions in the disc at the time of planet formation. At the same time the similarity in the timescales for disc dispersal and planet formation may also hint at the possibility that the planet formation process plays a part in the final dispersal of the discs (e.g. Rosotti et al. 2013, 2015).

The recent ALMA image of the disc around the young solar-like star TW Hya is a prime example of a disc showing hints of planets orbiting at tens of AU, co-existing with a inner gap at 1 AU which could have been recently created by photoevaporation (Ercolano et al. 2017). The ALMA image is shown in the lef panel of Figure 3 and was obtained by a team including members of this Research Unit (Andrews, et al. 2016). However both the existence of planets and the photoevaporated gap remain speculative at present. As shown in the right panel of Figure 3, current planet-disc interaction models fail to reproduce the shape of the gaps as obtained from scattered light observations taken with SPHERE (van Boeckel et al. 2016). Furthermore, while several spectral line observations exist for TW Hya, the photoevaporation models do not yet have the predictive power to directly measure the mass loss rate in the wind from them. Until that becomes possible, even the nature of the gaps and rings the nearest and best studied of all (pre-)Transition Discs, remain uncertain.

The inside-out dispersal of protoplanetary discs, forming TDs, is also an important factor to consider when studying the final architecture of exo-planetary systems. While planet migration is necessary to explain (e.g.) the presence of large planets close to the central star, the so-called “hot Jupiters”, this process alone cannot explain the pile-up and deserts in the semi-major axis distribution of exoplanets (see also Chatterjee & Tan, 2014, 2015). An additional planet-parking mechanism is required, which may be provided by (e.g.) photoevaporation which opens a gap in the disc, forming a TD and stopping further planet migration (e.g. Alexander & Pascucci 2012; Ercolano & Rosotti 2015).

3.2 Why is a Research Unit on TDs needed Now?

From the above argumentation it becomes clear that TDs are unique laboratory experiments created by Nature that allow us to test and update our understanding of disc structure and evolution as well as planet formation processes on the small scale (dust growth and dynamics) and large scale (planet assembly and planet-disc interaction).

New observational facilities including ALMA and VLT-SPHERE are revolutionising our view of TDs. We are now starting to obtain extraordinarily detailed images of these objects at infrared and millimetre wavelengths. While the new observations are fundamental to pin down many important characteristic of the dust and gas density distribution in the bulk of these discs or in their cavities, the disc atmospheres and winds, which bear the signature of the dispersal mechanism, are best traced by high resolution observations of emission line profiles. As well as a number of surveys which are in course on the VLT in the optical, the mid-infrared region will also see a wealth of new data with the upgrade for the CRIRES instrument, which has an an expected delivery date of 2019. A solid theoretical framework is thus urgently needed in order to interpret the new/future observations and decode the message encrypted in the spectral and continuum emission of TDs. The new models developed in this project are exactly what is needed at this stage. Furthermore, models for the formation and evolution of planetary systems are reaching new levels of complexity, but they remain limited due to the current uncertainties in the boundary/initial conditions inherent to uncertain disc physics.

Now that the era of high-resolution optical/infrared and (sub-)millimetre imaging is under way and starts revealing complex structures in these discs, the time is ripe for a concerted theoretical/numerical modeling counterpart to these observational studies. To be able to understand the observed features and statistics of TDs, this effort must combine the theory of disc structure, evolution and destruction with dust growth and dynamics, as well as with planet-disc interaction and dynamics. It can therefore not be done in a single or a set of DFG individual proposal, but requires a concerted, closely knit small network of projects involving several teams, covering the key observational and theoretical skills. To make the link to the observations of these disks, which are typically done in scattered light (optical/IR), dust thermal emission (sub-millimetre) and molecular rotational lines (sub-millimetre), our effort has to also include modeling of disc chemistry and radiative transfer, as well as team members with detailed understanding of the observations and their limitations. This is the motivation of the research group we propose here.

4. Contribution of this team to the field

Our team is composed by theorists and observers, who have all contributed significantly to the state-of-the art of the field today. On the theory side our team includes dynamicists, experts in radiative transfer, dust evolution and astrochemistry, who are committed to exploit the synergies of the team to provide a holistic approach to understanding planet formation and disc evolution, via the study of TDs and their formation.

Speaker: **Prof. Barbara Ercolano (LMU)** has been studying the link between high energy radiation from the central star and disc evolution and dispersal (e.g. Ercolano et al. 2008a, 2009; Owen, Ercolano et al. 2010, 2011, 2012). Before Ercolano et al. (2009), the importance of X-ray radiation from the central star on the dispersal of discs had not been recognised. This process is now accepted as one of the major player for disc dispersal, hence setting the timescale for planet formation. The models have been tested against observables (e.g. Ercolano et al. 2010; Owen, Scaife & Ercolano 2013; Koepferl, Ercolano et al. 2013; Ercolano, Koepferl et al. 2015), producing several successes, but also opening new questions (e.g. Ercolano & Owen 2016), such as those to be approached as part of the projects proposed here. Prof. Ercolano and her team have also investigated the effects of X-ray irradiation on the final parking radius of exoplanets (Ercolano & Rosotti, 2015), as well as on the intrinsic (Ercolano & Glassgold 2012, Mohanty, Ercolano & Turner, 2013) and observed accretion properties of protoplanetary discs (Ercolano et al. 2014). With the work of Rosotti, Ercolano et al. (2013, 2015) the interaction between planet formation and photoevaporation was first taken into account, in an attempt to match TDs statistics. Together with Prof. Testi, she recently published a Letter showing that the innermost gap in the closest planet-making disc to Earth, TW Hya, could be the first photoevaporative gap imaged. Prof. Ercolano is also the main author of the dust RT and photoionisation code MOCASSIN (Ercolano et al. 2003, 2005, 2008b), which is one of the main tools used for the subpojects in area B. This code includes X-ray processes and was recently ported to Voronoi grids (Hubber, Ercolano & Dale, 2016) For the development of MOCASSIN Prof. Ercolano received the Royal Astronomical Society Fowler Prize for early career achievements in 2010 (https://www.ras.org.uk/news-and-press/157-news2010/1713-ras-honours-outstanding-astronomers-and-geophysicists).

Co-Speaker: **Prof. Cornelis Dullemond (ZAH)** is an expert in modeling the radiative transfer in protoplanetary disks, to compute the (vertical) disc structure and the disk's appearance as seen by observational facilities. He is the author of the popular open source RADMC-3D radiative transfer modeling package, which he and his team employ to study protoplanetary disks, and linking models to observations at infrared and submillimetre wavelengths. He develops new methods for disc modeling, and has been involved in the development of new radiation hydrodynamics modules for the PLUTO code (Kuiper et al. 2010) and ZEUS (Ramsey et al. 2015). His group has also played a leading role in global disc modeling with dust growth and drift (e.g. Brauer et al. 2008; Birnstiel et al. 2010), the subsequent planetesimal formation (e.g. Drazkowska & Dullemond 2014), and the link between the disk/dust models and millimetre and infrared disc observations (e.g. Pinilla et al. 2014; van der Marel et al. 2013; Kataoka et al. 2015). A key theme in the research of Dullemond's group is the study of physical processes and how we can constrain them with observations. The group often develops its own methods of computation and own codes to implement the new physics in existing models, and thereby opening new directions.

Co-PI: **Prof. Wilhelm Kley (University of Tübingen)** is an expert in computational astrophysics with emphasis on the planet formation process, starting from the growth of small dust grains all the way to full grown planets. The numerical methods developed and used in his group range from molecular dynamics, smoothed particle hydrodynamics (SPH) and grid-based magneto-hydrodynamics (MHD) including radiative transport. These methods will be used in the theoretical modeling within the Research Group. One focus of his research has been on the important planet-disk interaction. Through multi-dimensional (2D and 3D) radiation hydrodynamical simulations his group demonstrated the possibility of strongly reduced or even outward migration (Kley & Crida, 2008; Kley, Bitsch & Klahr, 2009). Recently, models for the origin of the circumbinary planets have been presented (Kley & Haghighipour, 2014). Here, longterm models of disks in the presence of a central binary have been simulated and the motion of an embedded planet has been followed. Concerning the main focus of this research group, Müller & Kley (2013) constructed time-dependent hydrodynamics models of transitional disks induced by the presence of a single planet. Specifically, the models investigated the amount of gas flow past the planet into the inner hole as a function of the planet mass, disc parameter and stellar irradiation. With Picogna & Kley (2016) significant advances were made in the understanding of the dust phase response to planet-disc interactions.

Co-PI: **Prof. Paola Caselli (MPE)** is an expert on astrochemical modelling and observations of the earliest phases of star and planet formation. She has made important contributions on the chemical structure of pre-stellar cores (within which future stellar systems form.) She is now focusing on the link between molecular clouds and protoplanetary disks using high angular resolution observations, hydro- and magneto-hydrodynamical simulations, which incorporate various degrees of chemical complexity, and radiative transfer codes. She is interested in understanding the effects of different initial conditions in the physical and chemical evolution of protoplanetary disks. Already published work in this field include the chemical structure and ALMA observability of a self-gravitating disc orbiting around a protostar which will likely evolve into a future F-type main sequence star (Ilee et al. 2011; Douglas et al. 2013) as well as the chemical evolution of a self-gravitating disc surrounding a protosolar-type star (Evans et al. 2015). Using non-ideal MHD simulations of contracting dense cloud cores, she recently found that the disappearance of very small grains (VSGs), due to accretion onto larger grains, enables the formation of protoplanetary discs (Zhao, Caselli et al 2016). This is due to the fact that VSGs dominate the coupling of the bulk neutral matter with magnetic fields, thus allowing an efficient loss of angular momentum (via magnetic breaking) in regions where protoplanetary discs should form. Together with plasma physicists, she also started a detail study of dust grain charging and its effect on dust coagulation (Ivlev, Padovani, et al 2015). Her expertise on basic astrochemical processes will be applied to the available and future dynamical models of transition disks.

Co-PI: **Dr. Tilman Birnstiel (LMU starting in 02/2017)** has been studying the crucial early stages of planet formation by simulating growth, destruction, and global transport processes in disk (e.g. 8). While some of the transport processes have been proposed in the 70s, they were often neglected as they seemed incompatible with observations of disks. Birnstiels models were the first to show, that these processes are not only consistent with many observations but are necessary to explain and understand the evolution of disks (**?**). His models successfully explained or even predicted observed signatures of growth and transport processes: the spectral index behavior predicted in **?**) was observed in **?**), **(author?)**

(106) and others. Small scale pressure traps were needed to explain the integrated continuum emission properties of disks (**?**), which strikingly resemble the observations of **?**) and **?**). Sharp dust edges in protoplanetary disks as predicted in **?**) are now seen in almost every observation that has high enough resolution and sensitivity (e.g. **? ?**). Lately, for the first time, signatures of his predicted effect of dust accumulation inside the water snow line **(author?)** (8) have been detected in **?**). His models have substantial impact on the further evolution of planet formation via a range of effects: they provide the "pebbles" for pebble accretion, they predict how the planet forming material is redistributed within the disk, they determine the continuum opacity and therefore the temperature and observational appearance of disks, they feed the planetesimal formation factories and transport key volatile species along the way and finally they provide the surface area for chemical reactions that determine the chemical composition of the disk. To investigate these links to planet formation and to the disks chemical composition, he has been awarded an ERC starting grant that starts in March 2017, is hosted at the LMU, and perfectly complements the goals and work plan of this research group proposal.

On the observational side our group includes experts on the observations of young stellar objects, transition discs, initial stages of planet formation and planet disc interactions.Our observational team is experienced with state-of-the art observational facilities including: ALMA, IRAM-NOEMA and the VLA (continuum and spectroscopic interferometric observations) as well as optical/infrared high contrast imaging and spectroscopy using the LBT and the VLT instruments (in particular, but not limited to, XShooter and SPHERE).

Co-PI: **Prof. Leonardo Testi (ESO)**, has accumulated years of expertise in the observation and analysis of young stars and their protoplanetary discs at infrared and millimetre wavelengths. He has investigated the initial stages of planet formation via extensive studies of properties and evolution of dust in discs (e.g. Testi et al. 2003, 2014). With his group at ESO has completed the first large observational surveys for dust growth in disks (Ricci et al. 2010ab) and has developed the first self-consistent analysis tool to constrain dust properties as a function of radius in discs (Banzatti, Testi et al. 2011, Trotta, Testi et al. 2013, Tazzari, Testi, Ercolano et al. 2016). His group also developed the methodology to perform accurate measurements of the photospheric properties and accretion rates from broad-band XShooter spectra (Manara, Testi et al. 2013) and applied it to study the correlation between disc properties and mass accretion rates in young stars with disks (Manara et al. 2016). His current role as European ALMA Programme Scientist at ESO puts him in a very favourable position to lead an effort here in building a systematic catalogue of the available ALMA observations and help with the interpretation of these data in terms of the models. The new observational campaigns that we foresee for phase 2 of the Research Unit will also strongly benefit from his guidance.

Co-PI: **Prof. Thomas Preibisch (LMU)** has many years of experience in the fields of stellar X-ray astronomy and infrared observations of young stellar clusters. He was deeply involved in the Chandra Orion Ultradeep Project (COUP; see Preibisch et al. 2005), the Chandra Carina Complex Project (CCCP; see Preibisch et al. 2011), and numerous other projects where the identification of the X-ray sources with optical and infrared counterparts was a crucial step for the studies of the relation between the X-ray properties and the stellar/circumstellar properties of the young stars. He has also performed several large-scale surveys of star forming regions in the near-infrared (e.g., Preibisch et al.2011, Preibisch et al. 2014) and far-infrared regime (e.g, Preibisch et al. 2012) with the aim to identify protostars and study disk-bearing young stellar objects.

Collaborator: **Prof. Thomas Henning (MPIA)** is co-I on the VLT SPHERE disk programme and therefore has prime access to high-contrast high-resolution scattered light images of Transition Discs. He has been involved in many protoplanetary disc projects, both observationally and theoretically. He is co-author of the Klahr & Henning (1997) paper predicting the role of dust trapping in vortices in protoplanetary disks, something which has recently beensie observationally confirmed in transition disks. His involvement in this Research Unit will be through discussions/collaboration on the modeling and through comparison with the observations.

Collaborator: **Prof. Ewine van Dishoeck (MPE/Leiden)** is one of the founders of ALMA observatory. In recent years her group has focussed on studying Transition Disks with ALMA. In 2013 her team published the first strong evidence, based on ALMA data, for a dust-trapping vortex in the Transition Disk Oph IRS 48 and in 2016 her team found wide-spread evidence for dense molecular gas inside dust cavities. She has been involved in many protoplanetary disk studies, both observationally as well as from an astrochemical perspective. Her involvement in this Forschergruppe will be through discussions/collaboration on the modeling and through comparison with observations of the gas surface density structure.

5. Scientific Objectives

Planet formation and disc evolution feed back on each other. Indeed the formation and migration of planets in protoplanetary discs is clearly affected by the structure and the physical properties of the disc itself (e.g. Dürmann & Kley, 2016; Ercolano & Rosotti, 2015, to cite only a few of the works coming from our team). The structure and evolution of the disc, however, can be also deeply influenced by the planet formation process, as demonstrated by our recent calculations (e.g. Rosotti et al. 2013, 2015).

This has important consequences both in the interpretation of the observed exo-planet properties (eg. size and semi-major axis distributions) as well as in the interpretation of the disc structures, which are often used as tell-tale signs for planet formation, as in the case of the TDs. Our understanding of how the two processes influence each other is however still at incomplete. A more complete picture of planet formation and disc evolution is thus only possible with an interdisciplinary aimed at obtaining more holistic answers to a number of important questions.

Some of the key questions that will be addressed in the proposed Research Unit and the immediate objectives which relate to them are described in what follows.

5.1 First Main Question: How can we use TDs as direct witnesses of the planet formation process?

Which TDs are carved by planets and which are a result of disc evolution?

What do the complex shapes of TDs (rings, blobs, spirals) teach us about the physical and dynamical processes taking place in protoplanetary disks?

How does dust evolve and travel within discs to form planet(esimal)s?

To answer these questions we will use the following approach:

- *Investigate observationally the accretion properties and the distributions of dust and gas in the discs and winds of primordial compared to transition objects.* To this aim a systematic catalogue of observations will be built, which will provide the constraints to the modelling efforts described below.

- *Dust trapping and growth in TDs.* Dust and gas hydrodynamical models of discs with and without cavities will be produced to match the constraints from the observations, these will put constraints onto the planet-disc interaction and photoevaporation models described below.
- *Planet-disc interaction models with photoevaporation and dust trapping.* These models will aim at reproducing observations of (mainly) Type 2 TDs, including their accretion properties, to pin down the formation mechanism of the observed structures.

5.2 Second Main Question: How can we use TDs to learn about the disc dispersal mechanism?

What are the mass loss rates of the disc wind and what parameter space in the TD demographics can thus be reproduced by photoevaporation?
What are the dust and gas surface density distributions in TDs and how can they be explained?
How does the high-energy emission from the central star regulate disc accretion and dispersal, leading to the formation of different types of TDs?

To answer these questions we will use the following approach:

- *Determine the mass loss-rates of photoevaporative winds to pin down the mechanism producing Type 1 TDs.* To this aim appropriate wind diagnostics need to be identified via chemical modelling of photoevaporative winds, comparing primordial to TDs. Existing archival observations will be used at first to compare with the models and a new observing campaign with ALMA will be devised, perhaps spilling into the second funding period of the Research Unit.
- *Determine the dominant dispersal mechanism.* We will use the archival observations and the models from item 2.1 to analyse an initial sample of discs, the final statistics will be achieved however in the second funding period, where a population synthesis of (Type 1) TDs will be attempted.
- *Close the loop using mass loss rates, central star properties and accretion measurements to calibrate models.* At this point the models will have significantly less free parameters and can be used to extract the initial conditions for planet formation (e.g. mass, turbulence in evolved discs). This will make use of the new state-of-the art simulations and a homogeneous sample of accretion rates and central star properties including X-ray data.

6. Work plan

6.1 Overview over the Research Unit

The main goal of this Research Unit is to understand the morphology, spectroscopy and demographics of TDs, in order to answer basic questions about the planet formation process. We propose a four-pronged coordinated effort which includes (A) Observational studies; (B) Disc dispersal models; (C) Dust physics; (D) Planet-disc interaction models. The division in subfields is not strict and is only given here in the aid of clarity. Subfields often overlap and/or feed back on each other, highlighting the need of strong collaborations as proposed here. The observations will provide the constraints to be simultaneously met by models developed in the other areas. Our team is supported by several external collaborators in particular Prof. T. Henning (MPIA) and Prof. E. van Dishoeck (Leiden/MPE) have agreed to take an active part in our project. The theoretical models in the three theory subfields require expertise in hydrodynamics, astrochemistry, dust evolution and radiative transfer, which is available in our team. The specific projects in each area, the support required and the respective members of the team are summarised in the table below.

A	**Observations**		
A1	"Solids and gas evolution in disks: observational constraints"	2 PhD	*Testi, Ercolano, Preibisch*
A2	"New constraints about disc-dissipation processes from the relation between accretion and X-ray activity"	1 PhD	*Preibisch, Ercolano, Testi*
B	**Disc dissipation and chemistry**		
B1	"The radiation-hydrodynamics of photoevaporative winds with chemistry"	1 Postdoc	*Ercolano, Caselli*
B2	"Astrochemistry in the atmosphere and winds of photoevaporating discs "	1 Postdoc	*Caselli, Ercolano, Ivlev*
C	**Dust physics**		
C1	"Trapping the dust: Planet formation 'hotspots' in TDs"	1 PhD	*Birnstiel, Dullemond, Kley*
C2	"Gone with the wind: Dust entrainment in photoevaporative winds from realistic underlying grain distributions "	1 PhD	*Ercolano, Birnstiel, Dullemond*
D	**Planet-disc interactions**		
D1	"Transition disks and planetary systems"'	1 Postdoc	*Kley, Dullemond*
D2	"Origin of complex non-axisymmetric structures in type 2 Transition Disks "	1 Postdoc	*Dullemond, Kley*

Figure 2 shows schematically the direct links between the listed sub-projects, which provide the foundation for the Phase 2 study. Details about the major links between sub-projects are summarised in the next Section.

Area A: Observations

The projects in this area both aim at obtaining observational constraints on the dust and gas properties of protoplanetary discs and their central stars. Project A1 focusses on collecting and analysing existing ALMA data and complementing those with additional ALMA, VLA and high-contrast infrared imaging observations. The aim is to characterize the content and properties of solids and gas in TDs and to compare with the demographical properties of evolving disk populations. Evidence for dust and gas evolution, including grain growth, and planet-disc interactions will be characterised in order to provide direct observational tests of planet formation and dispersal theories, necessary to interpret the observational appearance of Type 1 and 2 TDs. The focus of project A2 is on the central star properties and their relation to the accretion properties of the disc, which may be modulated by the disc dispersal mechanisms that lead to the formation of TDs. While both of these projects have

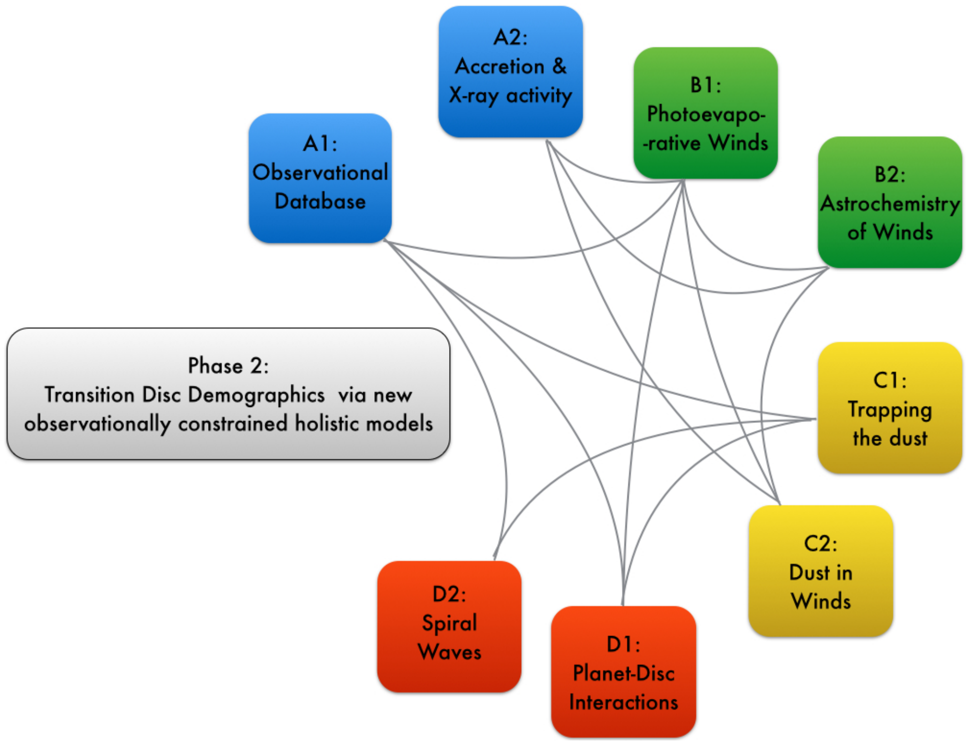


Figure 4: A diagram showing the links between the various projects. See text for detail.

self-contained aims, they will also provide the observational goalposts for the theoretical investigations of all projects in areas B, C and D, and indeed a legacy for future theoretical studies of this kind also by other groups.

Area B: Disc dissipation and chemistry

The main objective of the projects in this area is to determine the mass loss rates in disc winds, and constrain once and for all the disc dissipation mechanism, leading to the formation of Type 1 TDs. This is crucial to interpret the observed Type 1 demographics. We will perform quantitative spectroscopical modelling of disc winds, identifying and using new wind diagnostics, in particular comparing primordial and TDs. In project B1 we will develop the most comprehensive radiation-hydrodynamics models of photoevaporative disc winds to date. The physics beyond the X-ray heated layer will be accounted for for the first time. This will be achieved by coupling our (radiation-)hydrodynamics code, PLUTO, to an efficient chemical solver for a reduced network, developed in project B2. Project B2 aims at producing a detailed astrochemical model of the disc atmosphere and its wind. By means of radiative transfer calculations a synthetic spectrum will be obtained to be compared with state-of-the-art observation of spectrally revolved emission from discs, particularly those with known cavities (TDs). The intensity and profiles of emission lines tracing the base of the wind will allow us to put constraints on the wind-launching mechanism, responsible for the dispersal of the discs.

Both projects will use existing and new observational constraints coordinated in projects A1 and A2, and also provided by our external collaborators. The dust content of the wind which is of prime importance for the chemical modelling will be provided by project C2. Project D1 will inform us on planet-disc interactions which may help photoevaporation create gaps and holes at earlier times and may cause strong asymmetries, yielding different streamline architectures (see e.g. Rosotti et al 2013, 2015).

Area C: Dust Physics

The dynamics and evolution of dust grains in discs is the main subjects of this area. In project C1 we will study the growth and trapping of dust grains at hotspots in TDs that may lead to breaking through the meter-size barrier of radial drift, thus allowing the formation of planetesimals. We will use (radiation hydro)-dynamical modelling and dust coagulation models as well as 3D radiative transfer tools. Furthermore, we will be able to use the observational sample collected and analysed in project A1 to tackle fundamental open questions on the first stages of planet formation. This project will feedback and take inputs from the photoevaporation modelling performed in project B1 and it will eventually produce the underlying dust distributions for project C2, which aims at determining the dust content of photoevaporative winds. The latter will make use of state-of-the art models of photoevaporating primordial and TDs from project B1 as well as inputs for the dust distributions from project C1, in order to constrain dust entrainment in the wind, which is an important input to the chemical models in project B2. Finally, project C1 would highly benefit from the setups and methods developed in the more detailed models of Area D.

Area D: Planet-disc interactions

Projects in this area aim at constructing realistic simulations of planet-disc interactions and studying the dynamical processes leading to non-axisymmetric features in order to explain the wealth of new and intriguing observations of TDs. The overarching goal is to use these observation-constrained (from project A1) models to pin down the important details of the disc interaction processes. This is of fundamental importance to be able to disentangle the message about planet formation which is locked in TDs observations. In particular project D1 aims at significantly pushing forward the state-of-the art of (radiation)-hydrodynamical models of gap-forming giant planets embedded in discs including dust dynamics. This project will provide important inputs of gas and dust density distributions for project B1, particularly informing about the fate of dust grains at planet-gaps, which is also relevant to project C1. Project D2 aims at explaining the surprising non-axisymmetric structures recently observed with ALMA in a number of TDs, via detailed hydrodynamical and radiative transfer models, which will also account for realistic grain size distributions from project C1. Studying the intriguing nature of these objects is likely to provide important insights on planet-disc interaction processes, thus enabling us to use these discs as proxies for planet formation.

6.2 Future perspectives

While all sub-projects presented here are self-contained and will provide specific intermediate science products, the major strength of this program is the collaborative work to produce a holistic picture of protoplanetary disc evolution and dispersal, which through the study of TDs can be used to inform us on the planet formation process. At the end of Phase 1 of the Research Unit all theoretical models will have been significantly improved to allow a much more realistic approach to match the observational constraints. At the same time the systematic analysis of the existing observations and the collection of new data will have also provided a much clearer picture of disc structures, as possible planet formation signatures.

At the end of Phase 1 our team will be then perfectly posed to perform the most advanced simulations of individual objects, but also and perhaps more importantly, we will be able to tackle the issue of demographics of TDs. Via population synthesis models of TDs including disc dispersal, planet formation, dust evolution, some simplified chemistry and radiative transfer, we will be able for the first time to use discs to make predictive models of planet formation and evolution to match existing exo-planet statistics.

We thus foresee a two-pronged approach in Phase 2:

i) Detailed modelling of individual objects.
This will follow mainly from the joint work of areas A (in particular A1) and D, and will target mainly Type 2 TDs. The insights gained in Phase 1 of the Research Unit will allow us to construct tailored models of planet-disc interactions to explain specific observations of Type 2 TDs (not necessarily obtained by our group). The tailored models will allow us to decode the message in the many interesting new features highlighted already by spatially resolved observation, which, by the beginning of the second funding period, will have surely delivered more surprises.

ii) Statistical distributions/demographics of Type 1 TDs.
The work carried out in Phase 1 in areas A, B and C will have resulted in the most advanced disc dispersal models, which would have also been calibrated for important quantities with direct observations. We will use these models to construct population synthesis of Type 1 TD demographics (e.g. inner hole radius vs accretion rate), to compare with available surveys in individual clusters. This will be a very strict, direct test of our disc models, and will allow us to predict realistic initial conditions in a disc population at the time of planet formation and migration, which are fundamental inputs for planet formation models (the latter are however beyond the scope of this proposal).

It is inappropriate at this stage to design a more detailed program for a potential Phase 2 of the Research Unit. As well as depending on the outcome of our Phase 1 projects, the exact focus of a potential extension would depend on the developments of the field as a whole. Some general ideas go in the direction of providing the basis for more detailed chemical and physical evolution of Solar-Nebula-type discs, needed to gain a better understanding of the Solar System origin and composition, including the large variety of minerals and organics found in comets and meteorites.

6.3 Research Environment of the Research Unit

The new young Research Unit members will be welcomed in a stimulating environment, where complementary research programs are being carried out at all of the institutions involved.

At the LMU, Prof. Birnstiel's group (funded by an ERC starting grant) will focus on several aspects of dust evolution in planet-forming disks, with the aim of pushing the state-of-the-art of what is possible with current codes. Prof. Preibisch's group can provide support on observational aspects of high energy radiation from young stars. Prof. Ercolano's group comprises experts who are expert dynamicists and together with other Computational Astrophysics Group members (led by Prof. Burkert) will be able to provide extensive support for the numerical aspects of the projects. Prof. Ercolano is also a research area leader (Star and Planet Formation) at the Excellence Cluster "Universe", which hosts the C2PAP computing centre, which, as well as computing facilities, provides a team of professional code developers to be booked on a project basis. The coding support positions have been guaranteed by the LMU to be continued after the end of the Universe Cluster, independent of an eventual award for a new Cluster.

At the MPE Professor Caselli is the director of the Centre for Astrochemical Studies (CAS), where a large body of expertise on chemical networks and solvers exists.

ESO, the European Southern Observatory (or formally the European Organisation for Astronomical Research in the Southern Hemisphere), is the leading intergovernmental astronomy organisation in Europe, supported by 16 Member States, along with the host state of Chile. Its approximately 110 staff astronomers, 40 fellows and 40 PhD students conduct frontline research in fields ranging from exoplanets to cosmology. ESO's Star and Planet Formation group currently has a total of 19 staff members, 9 post-doctoral fellows, and 4 PhD students, producing over 300 publications since 2015. One of Leonardo Testi main areas of expertise is in infrared and submillimetre observations of protoplanetary disks. He is currently supervising the work of 4 postdoctoral fellows and one student in this scientific area. Young researchers and students at ESO enjoy full access to the Garching campus scientific life and infrastructure, including a rich portfolio of seminar series, direct access to state of the art computing facilities and expertise for the data reduction of millimetre and infrared observations. Leonardo Testi's group at ESO meets weekly on Thursday to discuss progress on internal projects and on Fridays, jointly with Paola Caselli's group at MPE, to review literature and discuss common interest projects.

At Heidelberg .... Kees - Heidelberg?? Yes, I will do that.

The prime research focus of the Computational Physics group in Tübingen is the formation of stars and planets. This includes an understanding of the physics of accretion disks, the origin of the turbulence, dynamics and growth processes of small embedded dust particles, planetesimal formation, planet migration, circumbinary disks. Additionally the groups interest lie in the field of computational astrophysics where new numerical methods are being developed and implemented which includes particle-based and grid-based approaches. The group presently hosts a Emmy-Noether research group on 'Massive star formation' with group leader Rolf Kuiper, who is an expert in implementing radiation transport algorithms in hydrodynamical codes. In total the group consists on average of about 15-20 young people providing an inspiring scientific environment.

The LMU hosted in 2012 the "Planet Formation and Evolution" conference (organised by Prof. Ercolano and Prof. Preibisch), the 8th in a series of conferences held regularly in Germany. In 2017 Prof. Kley, Prof. Ercolano and Prof. Testi are organising a 4-week long workshop on Disc evolution and Planet Formation at the Munich Institute for Astronomy and Particle Physics (MIAPP), in Garching bei München, which will bring together scientists from various theoretical, observational and experimental fields, with the aim to stimulate interdisciplinary discussion between astronomy, planetary science, mineralogy, laboratory work, and other adjacent fields. The proposed Research Unit will obtain high visibility through the workshop, which will also help find the best candidates for the available positions.

6.4 Interactions between projects and institutions

The projects planned are not only collaborative amongst institutions, but also present strong dependancies from each other, which is the motivation for setting up a Research Unit. Several members of the network already work regularly together, so we foresee that this compact network will benefit from close-knit collaboration amongst its members. As well as links between the projects we have also links between various institutions within one project, which are led by people from different institutions. We request a substantial budget for longer working visits so that students/postdocs will not work in just one institute, but effectively work in multiple. Furthermore, we foresee strong links between our groups and those of our external collaborators, in particular Prof. T. Henning (MPIA) and Prof. E. van Dishoeck (Leiden/MPE). Each group will reserve a workplace especially for such exchanges, both within Munich/Garching as well as across the cities. Furthermore, we plan to keep communications between teams in sub-projects as lively as possible. We foresee the following: (1) Kick off and Wrap up events at the start and end of Phase 1 of the Research Unit. These events will also be open to non-members, who may provide external support and collaborate on some of the projects; (2) Twice a year two days face to face meeting with all members at rotating locations amongst the institutes in the Research Unit; (3) Once a month a Video Conference amongst members of a given area, where the young researchers will present status reports of the various sub-projects. A concise summary of the meeting will then be compiled on a rotation basis by the students/postdocs in the area and then distributed to all members. (4) Collaboration meetings between individual projects.

6.5 Promotion of Early career researchers

We have requested a mix of PhD and Postdoc positions, the latter because of the complex computational aspects of some of the projects in this building phase of the Research Unit. We are very committed to the training and the promotion of young researchers, and indeed most of the Postdocs are planned to be junior positions (within three years of PhD). The nature of the projects themselves is favourable to the promotion of early career researchers by providing them with definite and clear science products as well as training them in highly sought-after skills, which will propel them in today's challenging academic world. The Research Unit with the thriving interactions and the teamwork towards a common goal also provide a perfect environment to develop a broad view of interrelated, but fundamentally different research areas, which will especially benefit PhD students and academically young postdocs. The postdocs will be encouraged and supported to develop independence, which will set them up on a career path to individual fellowships.

6.6 Gender Equality Measures

Our PI team is already relatively balanced in terms of gender. We will continue to work towards creating a still more balanced team of female and male PhDs and Postdocs in this Research Unit. We will also particularly stimulate women to apply for the theoretical research positions of our Forschergruppe, to amend the relative paucity of women in theoretical areas of (astro)physics.

6.7 Family Support Measures

Family support is of prime importance in our Research Unit, and we are aware of the complicated issues of work/family balance. In particular care will be taken in the scheduling of the biannual Research Unit meetings, which will necessarily involve traveling, in order to minimise disruption to family life. When possible we will use video-conferencing (e.g. for the regular monthly meetings), and will provide financial support to members who wish to travel with a caretaker for their small children for the face-to-face meetings, which we foresee to be at least twice a year (on top of the Phase 1 kick-off and wrap-up meetings), and for the longer collaboration visits.

7. Financial Overview

The total funds requested in all categories for all 6 projects are summarized in the following (all amounts in EUR).

Personnel

We request funding for 5 PhD students at 50& (E13/2) and 4 postdocs.

Projec t	Year 1	Year 2	Year 3
A1			
A2			
B1			
B2			
C1			
C2			
D1			
D2			
Total: (EUR)			

Consumables

No investment necessary

Publications

9 positions at 700 EUR 5600 EUR

Travel

The amounts for travel refers to money allocated directly to the individual projects, first to support longer term visits between the different closely collaborating nodes of the Forschergruppe, and second expenditures related to experimental studies that have to be conducted outside of the Forschergruppe. This money is in addition to that in project Z.

Project	Year 1	Year 2	Year 3
A1	4.046	4.046	1.368
A2	3.000	3.000	3.000
B1	4.000	5.600	5.600
B2	3.810	3.810	3.810
B3	5.100	6.700	6.700
B4	2.760	2.500	570
C1	2.820	2.820	2.820
C2	4.640	2.720	2.540
D1	6.129	6.129	1.356
D2	1.300	1.300	1.300
Total: (EUR)	37.605	38.625	29.064

Technical equipment

We request a multicore machine to carry out part of the theoretical work. This is necessary in particular for development work. The machine will be accessible to all members of the Research Unit. The cost per year of the machine (see attached quote) is 9750 EUR

Central Budget

The total funds requested for Project Z are summarized in the following table.

	Year 1	Year 2	Year 3
Networking	24.800	41,800	41,800
External Travels	30.000	30.000	30.000
External Guests	30.000	30.000	30.000
Conference/Summerschool	20.000	-	20.000
Consumables	1.000	1.000	1.000
Publications	5.000	5.000	5.000
Management (Bat Vb/2)	21.000	21.000	21.000
Total: (EUR)	131.800	128.800	148.800

Total Budget

Listing of total costs

Item	Year 1	Year 2	Year 3
Positions (PhD/HiWi)	277.000	274.750	264.000
Travel (projects)	37.605	38.625	29.064
Small Equipment	56.040	2.500	-
Consumables	43.598	41.190	29.440
Other Costs	23.450	12.450	7.250
Project P	80.000	80.000	80.000
Project Z	131.800	128.800	148.800
Total: (EUR)	649.493	578.315	558.554

8. Signatures

The project leaders have agreed to be responsible for the scientific work of their projects.

The Speaker and co-Speakers of the Forschergruppe: Planet Formation Witnesses and Probes: Transition Discs

Prof. Barbara Ercolano
University Observatory
Ludwig Maximilians University Munich
81679 München

Dr. Cornelis P. Dullemond
Institute for Theoretical Astrophysics
Ruprecht-Karls-University Heidelberg
69120 Heidelberg

Munich, December 30th, 2016

Barbara Ercolano Cornelis P. Dullemond

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