# Planet Formation Witnesses and Probes: Transition Discs

Speaker: Barbara Ercolano

Co-speaker: Cornelis Dullemond

# Participating institutes and principle investigators

- **Ludwig Maximilians University Munich (LMU):**
  - University Observatory
    *(Prof. Dr. Barbara Ercolano, Prof. Dr. Thomas Preibisch)*
- **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:**
  - Institut für Theoretische Astrophysik (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-speakers:**
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

# Summary

Recent surveys have shown an overwhelming diversity of extrasolar planetary systems, prompting the question of how some may end up looking like our own and being able to sustain life. The environment in which planets form plays a major role in this issue. 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 "TDs" (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 (up to several 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, 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 communities 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.


# 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.

The protoplanetary discs which surround young low mass stars provide the gas and dust from which planets may form. Therefore, understanding the evolution and final dispersal of these discs plays a central role in understanding the initial conditions and timescales of planet formation. For the largest part of their lives, the evolution of the surface density of discs is 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 recent 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). 'TDs' (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.

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, Dullemond and Hollenbach 2009, 2015). Photoevaporation is successful in reproducing the observed dispersal timescales, the inside-out mode of disc dispersal, and can reproduce a subset of the TD demographics.

However, disc dispersal by photoevaporation, while certainly an important piece of the puzzle, does not tell the whole story beyond 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 seems 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.

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 (e.g. Rosotti, Ercolano et al. 2013, 2015) or grain growth (Birnstiel, Andrews & Ercolano 2012) models to date, and the classical explanation is that these objects may have instead been carved by dynamical interactions with a forming giant planet (e.g. Zhu et al. 2011). ALMA now allows to measure the bulk of the molecular gas *directly*, showing than many Type 2 TDs have dense gas inside the dust cavities (van der Marel et al., 2016), in agreement with the planet scenario. 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 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. 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?

Both types of TDs can thus provide complementary information about the planet formation process, as they 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 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, Ercolano et al. 2013, 2015). 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).

**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). 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. And 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.

# 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.

*Speaker:* **Prof. 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. Prof. Ercolano is also the main author of the dust RT and photoionisation code MOCASSIN (Ercolano et al. 2003, 2005, 2008b; Hubber, Ercolano & Dale, 2016), which is one of the main tools used for the subpojects in area B. 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. 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. 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. 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:* **Prof. 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.

*External Collaborator:* **Prof. T. 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 been 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.

*External Collaborator:* **Prof. E. 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. She co-leads a large ALMA proposal on Transition Disks. Her involvement in this Forschergruppe will be through discussions/collaboration on the modeling and through comparison with observations of the gas surface density structure.

# Scientific Objectives

In the proposed Research Unit we will address the following two questions:

1. **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?

2. **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 are the processes of disc accretion and disk dispersal, leading to the formation of TDs, influenced by the high-energy emission from the central star?

In order to answer these questions we have designed a novel strategy to tackle the interrelated problem of disc evolution and planet formation, which conspire to produce the diverse population of TDs observed. Our project exploits the unique synergies amongst the theorists and observers in our team. Respectively, the following **immediate objectives** relate to the questions set above:

**1.1 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.

**1.2 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.

**1.3 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.

**2.1 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.

**2.2 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.

**2.3 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.

# Work plan

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 evolution in disks: observational constraints" | 1 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 | "Disc mass loss from quantitative spectroscopy of photoevaporative winds" | 1 Postdoc | *Ercolano, Caselli, Dullemond, Kley* |
| B2 | "Essential astrochemistry of disc winds" | 1 Postdoc | *Caselli, Ercolano* |
| **C** | **Dust physics** | | |
| C1 | "Trapping the dust: Planet formation 'hotspots' in TDs" | 1 PhD | *Dullemond, Kley, Ercolano* |
| C2 | "Gone with the wind: Dust entrainment in photoevaporative winds from realistic underlying grain distributions " | 1 PhD | *Ercolano, Dullemond* |
| **D** | **Planet-disc interactions** | | |
| D1 | "TDs and planetary systems"' | 1 Postdoc | *Kley, Dullemond* |
| D2 | "Origin of complex non-axisymmetric structures in TDs " | 1 Postdoc | *Dullemond, Kley* |

Figure 1 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 and EVLA observations. Evidence for 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 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.

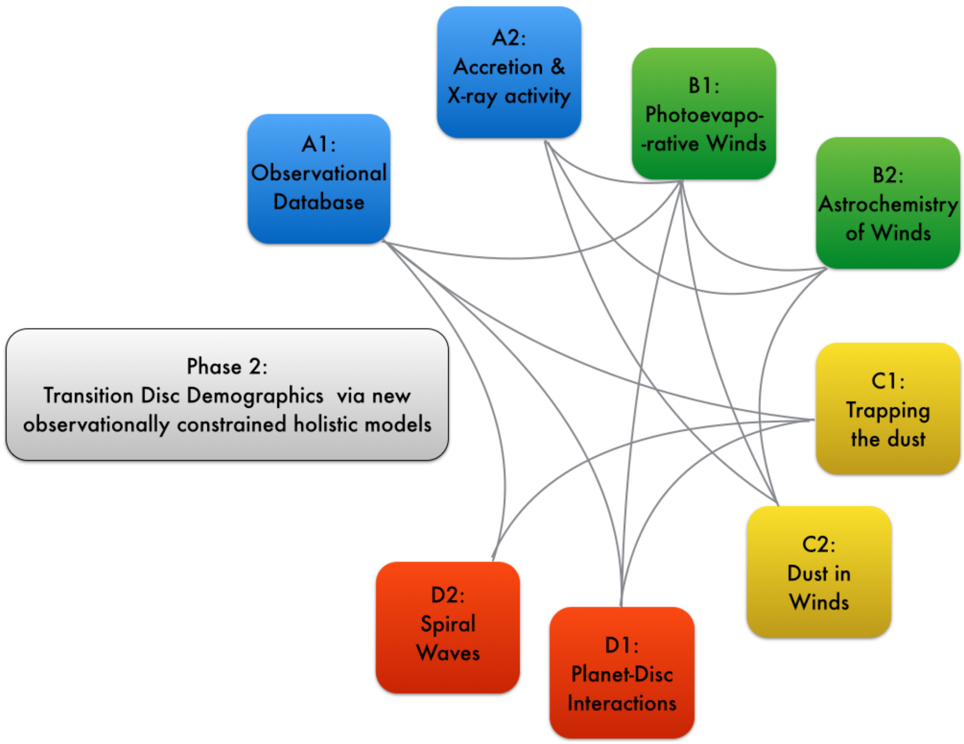


Figure 1: A diagram showing the links between the various projects. See text for detail.

**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 make use of a newly developed hydrodynamics, photoionisation and radiative transfer models, self-consistently linked to astrochemical models of the wind, developed in project B2. The projects aim at matching existing and new observational constraints coordinated in projects A1 and A2, and also provided by our external collaborators. The dust content of the wind is also of prime importance for the chemical modelling and will be constrained in project C2. Planet-disc interactions may help launch winds at earlier times and may cause strong asymmetries, which will yield different streamline architectures (see e.g. Rosotti et al 2013, 2015), from which we will be informed by project D1.

**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 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 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 projects B1 and B2.

**Area D: Planet-disc interactions**

Projects in this area aim at constructing realistic simulations of planet-disc interactions 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 important details of planet-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. This project will provide important inputs of 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.

***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.

***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.

***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.

***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.

***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 their families 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.

# Project A1: Solids evolution in disks: observational constraints

**Authors:**

PI: L. Testi (ESO)

Co-I: B. Ercolano (LMU), T. Preibisch (LMU), T. Henning (MPIA),

Collaborations: H. Baobab Liu (ESO), J.M. Carpenter (ALMA), G. Guidi (INAF/UniFi), I. Pascucci (Arizona), A. Natta (DIAS/INAF), M. Tazzari (LMU/ESO), J.P. Williams (Hawaii), E. van Dishoeck (Leiden, MPE)

**Requested positions: 1PhD student**

**Abstract:**
This project aims at obtaining observational constraints on the dust and gas properties of protoplanetary discs as a function of evolutionary stage (e.g. primordial to transition) and the physical properties of the central star. We will analyse systematically the ALMA observations of young stars with discs in nearby star forming regions already collected as part of a series of programmes and we will complement these with additional ALMA and EVLA observations. We will firmly characterize the level of grain growth in discs as a function of stellar mass, evolutionary stage and morphology of the disc, and we will search for evidence of disc-planet interaction in the discs structure and kinematics of transitions discs. We will provide direct observational tests of different planetesimal formation theories and how/if they apply in different environments.

**Scientific background:**
Grain growth is a stage of planet formation that can be directly observed due to the effects on particle emissivity. Planetesimals and early planetary cores formation are difficult to probe observationally, while growing planetary bodies can be studied through their influence on the disc structure or directly imaged in the outer disc, when sufficiently young and large.

Submillimetre and centimetre wave observations over the last decade have established that grain growth occurs very early in the protoplanetary discs lifetime, large grains and pebbles are present in discs throughout their lifetime. This is at odds with simple grain evolution theories in gaseous discs, and several ideas have been put forward to explain this fact. Modern theoretical models require large grains confinement in specific regions of the disc associated with local pressure maxima in the gas phase transitions of abundant molecules (snowlines), or regions with very low gas to dust ratio. The new ALMA high angular resolution observations of the protoplanetary discs suggest that small rocky proto-planets may form early and help trapping millimetre and centimetre-size grains in discs (HL Tau, ALMA Partnership 2015).

ALMA now offers for the first time the sensitivity and angular resolution to observationally constrain these processes in large samples of discs and as a function of stellar and disc parameters, and, critically for this project, understand the role and properties of TDs in the context of the evolution of the wider disc populations.

**Scientific objectives:**
We plan to (i) derive dusty disc physical parameters (mass, radius, grain growth, morphology) as a function of the central star parameters (mass, age) and environment; and (ii) establish the fraction and properties of TDs, as members of evolving disc populations.

**Strategy of the proposed project:**
As part of the first four cycles of observations ALMA has observed or will soon observe a large fraction of the protoplanetary discs in the nearby star forming regions 850 $mu$m and/or 1.3 mm, both in the continuum dust and in the molecular line gas emission. These wavelengths are ideal to provide the maximum sensitivity to derive the structure of the dust and cold gas distribution. We are part of four large surveys that will provide sensitive and high angular resolution ($\leq 30-40$ AU) observations for almost complete (>90%) samples in the Cha I (executed in Cycle 2), Lupus (executed in Cycle 2, followup at a second frequency to be executed in Cycle 3), $\sigma$-Ori (scheduled at high priority in Cycle 3) and R CrA (scheduled for Cycle 3). Additional ALMA projects have already populated the ALMA Archive with observations for almost complete samples in Upper Sco and Taurus, and for a significant fraction of the Orion Nebula Cluster. Our role

in these collaborations is to study the dust properties using multi-wavelength observations and analysis tools and we are responsible for the long wavelength and high angular resolution followups (proposals have been submitted for ALMA Cycle 4 with PIs: Tazzari, Testi and Guidi), in addition, the R CrA survey is led by one of the ESO Fellows in our group (Baobab Liu).

As part of the PhD thesis of M. Tazzari (supervisors L. Testi and B. Ercolano), we have developed a new Bayesian analysis toolkit for interferometric observations of discs (Tazzari et al. 2016). The toolkit is very efficient and allows fitting of the disk structure at a single wavelength, also including complex prescriptions for the mass distribution in the disc (see e.g. the application in Guidi et al. 2016), as well as multiple wavelength disentangling the dust properties from the disc structure (Tazzari et al. 2016). The tool has been successfully tested with ALMA datasets (Testi et al. 2016, in press) and we will use it to extract disc morphological (e.g. disc radius, inner hole presence and properties) and physical parameters (e.g. mass, dust surface density distribution), which we will correlate with the properties of the central star and of the star forming region to derive evolutionary trends using statistically significant samples and uniform analysis tools. Some key results that we expect to extract are: the $M_{disk}$-$M_{star}$ and $M_{disk}$-$M_{acc}$ relationships, and the inner hole presence and size statistics in each of the star forming regions and their possible dependence with age. Ercolano et al. (2014) demonstrated that such relations may be driven by disc dispersal and hence from the emission properties of the central star. We will therefore closely collaborate with project A2 which can provide us with inputs and constraints with regards to stellar properties.

We will also extend the ALMA surveys to longer wavelengths, e.g. at 3 mm with ALMA or $\sim$10 mm with the EVLA, to systematically investigate the dust properties in discs. These studies have already started for some sub-samples in Taurus and Chamaeleon, but we have also submitted proposals to extend them in future ALMA cycles starting from Cycle 4 (2016/2017). We aim at establishing a relationship between the dust growth properties (level of growth and degree of concentration of the large grains) with the disc physical (eg. surface density profile) and evolutionary (age of the central star, disc morphology) parameters. These correlations are expected by global dust evolution models, but have never been observed, because of limited samples and noisy data, two limitations that our programme will remove.
We will proceed in the following way:

1. we will re-calibrate all the available datasets, including the application of non-standard self-calibration whenever possible; this will include about four-hundred protoplanetary disc sources in nearby star forming regions that will all be available to us either from our own programmes or through the ALMA Archive by the end of 2017;

2. we will apply systematically our new analysis tool to derive disc physical parameters (mass, surface density distribution, disc morphology); we will correlate these properties with the properties of the central star and the age/environment of each star forming region;

3. we will extend the ALMA surveys to longer wavelengths to constrain the grain growth process and derive its correlation with the discs properties and evolutionary stage.

All these steps are feasible and we are equipped with the tools to execute them. Although the success of all observing proposal cannot be guaranteed, we have a good track record of obtaining observations for the study of grain growth in discs and for the Lupus cloud we will have dual frequency data by the end of 2016 (with a proposal for a third dataset submitted in Cycle 4).

A key outcome of this effort will be the detailed characterization of the dust emission from the population of TDs in each region in comparison with the full disc populations. This information will be critical in understanding the role of TDs in these evolving populations. TDs appear to be a minority of each population, but the key question is whether their properties are similar in different environments and whether they represent a common, but brief phase of disc evolution.

As part of our project we will setup a database of ALMA observations of discs and their derived parameters that will be used by the whole collaboration and will be made available on the web in incremental releases as the data will be published.

**Links to the other projects:**

We will strongly rely on the stellar properties derived as part of subproject A2. The theoretical interpretation of our observational results will rely on the models developed as part of subprojects B1, C1, C2, D1, D2.

# Project A2: New constraints on disc-dissipation from the relation between accretion and X-ray activity

**Authors:**
PI: Thomas Preibisch (LMU)
Co-PI: Barbara Ercolano (LMU), Leonardo Testi (ESO)
Collaborations: C. Manara (ESA)
**Requested positions: 1 PhD Student**

**Abstract:**
We want to test models of X-ray driven disc photoevaporation leading to the formation of Type 1 TDs by using new observational data to study the relation between accretion rates of young stars and their X-ray emission. The aim is to combine the numerous available high-quality X-ray data of young stars in different regions with new and highly reliable accretion rates that can be derived from the new spectroscopic data on these stars. In this way, we will be able to study the relation between X-ray emission and accretion with much larger samples (hundreds of stars rather than just a few dozen) and for different regions spanning a range of ages, and to test the predictions of theoretical models of X-ray driven disc photoevaporation and the corresponding effects on the disc accretion rate. This is of fundamental importance to understand the formation and residual accretion rate distribution of Type 1 TDs.

**Scientific objectives:**

In this project we want to investigate the relation between the high-energy radiation from young stars and the evolution and dispersal of their circumstellar discs, via the formation of Type 1 TDs. According to theoretical models, the high energy radiation in the UV and X-ray regime plays a central role for the dissipation of the discs via the process of photoionization (Ercolano et al. 2008, 2009; Owen, Ercolano et al. 2010, 2011, 2012). On the other hand, the accretion of disc material from the disc to the star, which is thought to happen through magnetospheric funnels, is expected to influence the structure and properties of the stellar corona, where (most of) the stellar X-ray emission comes from.

Numerous X-ray observations obtained during the last decades have clearly established that young stellar objects (YSOs) in all evolutionary stages from protostars to the ZAMS stars show highly elevated levels of X-ray activity, typically 1000 times higher than seen in our Sun. Several observations also provided indications that the X-ray luminosities of young stars might depend on the presence and the properties of accretion discs. While these earlier studies suffered from small sample sizes, incompleteness of the X-ray detected samples, and ambiguities about the disc properties, the particularly deep X-ray observation of the Orion Nebula that was performed in the context of the Chandra Orion Ultradeep Project (COUP; see Preibisch et al. 2005) provided a fundamental clarification of these issues. The COUP data showed unambiguously and in a statistically significant way that the absolute as well as the fractional X-ray luminosities of accreting young stars are systematically *lower* by a factor of $\sim 2-3$ than the corresponding values for non-accreting stars. The COUP data also suggested that the fractional X-ray luminosity of the young stars may be anti-correlated with mass accretion rate, but this correlation could not be proved in a statistically significant way because the number of stars for which estimates of the accretion rate were available at that time was too small.

Different theories predict different relations between X-ray activity and mass accretion rate.

Theory 1: Accretion suppresses coronal X-ray activity. One possibility is that changes in the coronal magnetic field structure by the accretion process lead to lower X-ray emission. Another possibility is that the stripping of the coronal magnetic field by the interaction with the disc reduce the coronal volume and thus the X-ray emission. A further suggestion was that the magnetospheric coupling between the disc and the stellar surface might reduce the amount of differential rotation in the star, and thus reduce the efficiency of the dynamo action (and the magnetic activity). However, these kind of theories cannot make testable predictions: A putative reduction of the X-ray luminosity depends sensitively on the details of the interaction, thus essentially introducing scatter in the relations between X-ray and accretion properties.

Theory 2: Coronal X-ray modulate accretion. Drake, Ercolano, et al. (2009) use the X-ray

heated disk models of Ercolano et al. (2008a, 2009) to show that photoevaporative mass-loss rates are strongly dependent on stellar X-ray luminosity and sufficiently high to be competitive with accretion rates. Photoevaporation disrupts then accretion by lowering the surface density in the disc, causing a "Photoevaporation starved accretion phase" before the formation of a Type 1 TD. This theory predicts an inverse linear relation between accretion rates and X-ray luminosities.
Theory 3: The observed accretion rates depend on the final dispersal mechanism. Ercolano et al. (2014) suggest that the photoevaporation-starved accretion period is too short to be detected. What is most likely detected, instead, is the lowest possible accretion rate that a disc achieves before the formation of a Type 1 TD. Indeed viscous theory predicts a power law evolution with time of the accretion rates, meaning that discs spend most of their lives at the lowest possible accretion rate, which must then roughly equal the wind rate. This model then predicts that the observed accretion rates should be directly proportional to the X-ray luminosity, since the latter are directly proportional to the wind rates (Owen, Ercolano et al. 2010, 2011, 2012).

Theories 2 and 3 both imply that the stellar X-ray activity controls the evolution of the disc, and thus directly influences the formation and accretion demographics of Type 1 TDs.

In recent years, reliable accretion rate determinations have become more readily availble, thanks to the advent of new powerful spectrographs like X-SHOOTER at the VLT, that combine high spectral resolution with a wide wavelength coverage (the entire optical and near-infrared range, in the case of X-SHOOTER). Several spectroscopic surveys have been performed in the last few years or are ongoing in different star forming regions.

The main problem with most previous accretion rate estimates was that they were usually based on color excesses or equivalent-width determinations of single tracer lines (such as H-alpha or Ca). The other important parameters, i.e. the stellar effective temperature and the extinction, that are needed to convert color excesses or equivalent-widths to accretion rates, had to be derived from separate observations, or (more usually) collected from the literature. This combination of different observational data could easily lead to substantial uncertainties in the derived accretion rate estimates and the stellar parameters. The most important advantage of the new high-resolution wide-wavelength range spectra is that they allow a self-consistent and simultaneous determination of all the important parameters, i.e. the stellar effective temperature, the extinction, and the accretion rate, at the same time and from one coherent data set. This results in a far more reliable determination of accretion rates (see Manara & Testi 2014).

**Strategy of the proposed project:**

In this project, we aim at combining the numerous available deep X-ray observations of young stars in the Chandra and XMM data archives with new measurements of the accretion rates. This will result in a much larger sample to perform a detailed statistical analysis of the relation between X-ray activity and accretion in mass- and age-stratified samples of young stars.

First we will use the accretion rates determined for $\sim 700$ young stars in Orion from Manara et al. (2012) and compare them with the available X-ray data from the COUP project.

In the second part of the project we will use the existing X-SHOOTER spectra for numerous young stars in various regions and derive new and self-consistent measurements of the stellar parameters and the accretion rates. These data will be combined with Chandra and XMM data. In the course of the project, we also plan to perform new observations with X-SHOOTER in order to extend the spectroscopic sample and to optimize the overlap with the X-ray observations.

In oder to address the problem of the time variability of accretion rates, we will conduct photometric multi-color monitoring of selected regions (e.g., the Orion Nebula Cluster) with our (LMU) 2m Wendelstein Telescope. Our new wide-angle camera WWFI (providing a 0.5° field-of-view) is ideally suited for this. Taking 2–3 exposures in 3 filters every clear night will yield a comprehensive database for the characterization of the accretion variability of individual stars.

This will finally allow us to perform detailed statistical analysis of the relation between X-ray activity and accretion in mass- and age-stratified samples of young stars in different young clusters. The results will provide crucial new constraints for theoretical models of the X-ray-disk interaction and draw conclusions on the expected accretion rates distributions of TDs.

**Links to the other projects / collaborations:** The stellar properties are necessary for A1, B1 and C2. The accretion properties are needed to constrain the models in B1.

# Project B1: Disc mass loss from quantitative spectroscopy of photoevaporative winds

**Authors:**

| | |
|---|---|
| PI: | B. Ercolano (LMU) |
| Co-I: | P. Caselli (MPE), K. Dullemond (Heidelberg), Kley (Tübingen) |
| Collaborations: | T. Preibisch (LMU), L. Testi (ESO), James Owen (Princeton), E. van Dishoeck (Leiden, MPE), T. Henning (MPIA) |


**Requested position: 1 Postdoc**

**Abstract:**
Type 1 TDs are likely discs in an advanced stage of dispersal. The dispersal mechanism of discs is of fundamental importance to planet formation, yet the responsible mechanism is still largely unconstrained. Photoevaporation from the central star is currently a promising avenue to investigate. We aim at building the most up-to-date radiation-hydrodynamical calculations of irradiated discs coupled to photoionisation, chemistry and radiative transfer calculations to allow us for the first time to perform quantitative spectroscopy of disc winds. Comparison with existing observations will allow us to constrain mass loss rates and emission regions of the wind which will pin down the underlying driving disc dispersal mechanism.

**Scientific background:**

Understanding disc dispersal is a key piece in the puzzle of planet formation. Type 1 TDs, which are considered to be objects on the verge of dispersal provide a tight constrain on the underlaying dispersal mechanism. One of the favourite models to drive disc dispersal is photoevaporation by radiation from the central star (e.g. Clarke et al. 2001, Alexander et al. 2006). The exact nature of the driving radiation is however still open to debate. (Extreme and Far) Ultraviolet (UV) radiation as well as X-ray have been shown to be able to drive winds from the disc upper layers (Alexander et al. 2006; Gorti, Hollenbach & Dullemond 2009; Ercolano et al. 2009; Owen et al. 2010) able to disperse the discs in the observed timescales. However both the location and intensity of the wind depend strongly on the driving radiation, with differences of more than two orders of magnitude for mass loss rates predicted by different models. This has profound implications for disc evolution and hence for the formation of planets and their subsequent evolution (e.g. Ercolano & Rosotti 2015).

While the presence of disc winds has been confirmed via the observation of a few km/sec blueshift in the line profiles of a number of tracers like [NeII] 12.8$\mu$m and [OI] 6300 (e.g. Pascucci et al 2007), these lines cannot be used to infer the underlying mass-loss-rate (e.g. Ercolano & Owen 2010, Ercolano & Owen 2016). Mid-infrared observations of molecular lines (e.g. CO) provide a new promising alternative to directly measure disc winds. Indeed recent observations suggest that these lines may be tracing a disc wind which is slow and partially molecular (e.g. Pontoppidan et al. 2011; Brown et al. 2013). More observations of this type are planned after the update of the CRIRES instrument, which is expected to be completed by 2019. Observations with ALMA in molecular lines like e.g. CO J = 2-1 and J = 3-2 emission are also able to trace the presence of a wind (e.g.Klaassen et al. 2013, 2016). Molecular lines are sensitive to the mass loss rates since they sample a significant area of the wind launching regions. However the exploitation of molecular tracers is currently severely hampered by the lack of a suitable hydrodynamic wind model coupled to chemistry and to dust evolution models (which dominate the opacity in the wind) to interpret the observations. While a number of chemical models exist of the deeper, denser regions of discs, no model is currently available for the optically thinner disc winds. The work of Gorti & Hollenbach (2009), while carrying out detailed chemical calculations extending to the disc atmosphere, used a hydrostatic disc model which was analysed in a 1+1D fashion. Without hydrodynamics no predictions on line profiles can be made.

In this project we aim at searching for new reliable wind diagnostics. To this aim we will to perform chemical calculations of disc winds, to determine ionic and molecular abundances. We will then execute radiative transfer calculations of the most promising transitions.

We have performed the only existing radiation hydrodynamic calculations of X-ray driven photoevaporative winds to date (Owen et al. 2010, 2011, 2012). We have used these grids to make predictions on the ionised phase of the wind spectra (Ercolano & Owen 2010; Ercolano & Owen 2016), however the parameter space available to date is very limited. In this project we will significantly expand on this by constructing a library of X-ray wind solutions for an extended grid of X-ray luminosities and stellar masses, covering all observed values. We will then perform the first simultaneous chemical calculations in the wind and upper disc atmosphere.

Type 1 TDs, are particularly interesting as the streamline architecture of their winds and the profiles of the lines that are produced in the wind differ from those of primordial discs. (e.g. Ercolano & Owen 2010). Indeed the lines are expected to be broader and brighter for e.g. inner cavities of a few to 10 AUs. A quantitative spectroscopic comparison between TDs and primordial disc is also likely to provide important constraints on the wind architecture. Finally, the recent suggestion (e.g. Marino et al. 2015, Montesino et al. 2016) that some Type 2 TDs may have a tilted inner disc is an interesting avenue to explore. A tilted inner disc may strongly influence photoevaporation by allowing radiation to reach outer disc regions and may produce the large inner holes of (some) Type 2 TDs. This is certainly a worthwhile new challenge requiring the development of 3D simulations.

**Scientific objectives:**

The main aim of this project is to identify new wind tracers and use them to constrain mass loss rates and hence disc dispersal models.

**Strategy of the proposed project:**

We have divided the work load into two connected blocks which also have self-contained immediate objectives. Block 1 is already being executed by Dr Picogna, employed on a LMUExcellent initiative grant awarded to B. Ercolano in support of this project.

**Block 1: Parameter-space investigations of X-ray photoevaporation models.**

The 3D hydrodynamical code PLUTO is being modified to include the effects of X-ray irradiation (Owen et al. 2010) in order to produce a library of X-ray wind solutions that will be analysed in Block 2 As a further step we plan to perform a small set of 3D simulations to explore the effects of asymmetries in the inner disc. We expect to see dramatic effects in the photoevaporation profile and in the wind architecture, which may lead to the formation of large hole TDs. This avenue is never been explored before.

**Block 2: Spectral line energy distribution calculations of disc winds.**

The MOCASSIN code (Ercolano et al. 2003, 2005, 2008b), which has already been used to calculate the emission line spectra from the ionic phase of X-ray winds (Ercolano & Owen 2010; Ercolano & Owen 2016). The code has now been coupled and benchmarked to the KROME code (Grassi et al., 2014) to perform arbitrary chemical calculations (Ercolano & Grassi 2016, in prep) and needs now only the appropriate reduced chemical network, which we will obtain from B2.

The new KROME-coupled MOCASSIN code will be employed to perform photoionisation and chemical calculations disc wind solutions starting off from the available models of Owen et al. (2010, 2011, 2012) and then moving to the new data obtained in Block 1 (which is already being executed). To this aim, under the guidance of Prof Caselli, an initially very simple network will be included in the MOCASSIN-KROME to perform initial test calculations, which will then be updated when project B2 begins to provide results. As a final step we will perform 3D radiative transfer calculations to produce line intensities and profiles to compare with existing and new observations, which may become available at the time.

**Risk Assessment:** As it is currently unknown which diagnostic may directly be related to wind rates and profiles, this is potentially risky project. However we have hints from MIR observations that such diagnostics exist, and our approach is unique in finding them. This is also a high gain part of the project, since the direct measurement of wind rates and profiles would solve the disc dispersal problem once and for all, bringing about a real breakthrough in this field. If no suitable diagnostic can be found to directly invert emission lines to mass loss rates, we will calibrate the emission line measures using radio emission diagnostics (e.g. Owen, Scaife & Ercolano 2013). With regards to its dependance on the delivery of a chemical network from B2, some of the aims of B1 could also be obtained with simple (toy) networks, which could be successively updated.

**Links to the other projects / collaborations:**

This project depends on project B2 for the reduced network and on project A2 for the observational input. Furthermore Dr James Owen (Princeton) will be heavily involved in the project.

# Project B2: Essential astrochemistry of disc winds

**Authors:**
PI: P. Caselli (MPE)
Co-I: B. Ercolano (LMU)
Collaborations: W.-F. Thi, L. Szucs (MPE)

**Requested positions: 1 Postdoc**

**Abstract:**
Protoplanetary discs lose mass via a slow disc wind, probably driven by photoevaporation from the central star. A thermochemical study of this important component of young stellar object does not exist to date. The study of the chemistry in disc winds however relies on a knowledge of the opacities, which are largely dominated by small dust grains which are entrained in the wind from the underlying disc at the launch point. In this project we plan to develop a reduced chemical network appropriate for photoevaporative wind conditions and couple our chemical codes to space and time-varying dust distribution obtained in project C2. We will for the first time be able to draw detailed chemical profiles of photoevaporative winds, which is of fundamental importance to identify and interpret new spectral line diagnostics in existing and upcoming observations.

**Scientific background:**

Chemical models of gas in the protoplanetary and TDs are essential to pin down the initial conditions of the gas and dust from which planets form. Several sophisticated models have been and are continuously being developed to interpret the recent (e.g.) Herschel and ALMA observations of discs (e.g. Bruderer et al. 2015; Thi et al. 2013; Aresu et al. 2012; Meijerink et al. 2012; Woitke et al. 2010). These models however deal only with the dense parts of the discs, in rare cases extending to the bound disc atmospheres. No chemical model of a photoeveaporative disc wind exists to date. This is a serious shortcoming for the identification of suitable wind tracers and more importantly wind diagnostics, to guide new observations and constrain disc dispersal models (see discussion in project B1).

The physical conditions valid for material in the bound disc itself are not appropriate at all for a disc wind. First of all winds are much less dense than the material in the bound discs. Even in the case of vigorous X-ray driven winds, the densities at the base of the wind are rarely above ten million hydrogen atoms per cubic centimetre, and they decrease roughly with the square of the distance (i.e. they behave roughly like Parker winds, see e.g. Owen et al. 2010; Font et al. 2004). The opacity in the wind is further reduced because of the decrease in dust content, as only a fraction of the grains contained in the underlying disc are entrained in the wind (see Owen et al. 2011b and discussion in project C2). For these reasons molecules may have a much shorter lifetime and indeed parts of the gas in the wind will be completely photodissociated. For such physical conditions processes like surface chemistry, freeze-out etc. are not important, yielding a simpler problem, which bears less uncertainties compared with chemical models for colder and more opaque material in the bulk of the disc.

**Scientific objectives:**

Devise a chemical model appropriate for photoevaporative wind conditions which takes into account of the varying dust properties in the wind.

**Strategy of the proposed project:**
The project will develop along a three-stage path of growing complexity. It is possible that some of the tasks in stage three may be carried over to the next funding period. The three stages can be briefly described as follows:

1. A first task for this project is to simplify the gas-grain chemistry by reducing the chemical network to the minimum number of reactions needed to properly follow the formation/destruction of important species (in particular Hydrogen, Carbon, Oxygen as well as simple C-, O-bearing molecules) and the electron abundance or ionization fraction. The PI of this project has extensive experience in devising efficient but reliable reduced networks (see e.g. Keto, Rawlings & Caselli, 2014).

The reduced chemical network will be benchmarked against comprehensive chemical networks to make sure that the abundances of important (diagnostic) species such as C+, C, O, CO are well reproduced in the range of conditions appropriate for evolved and transitions discs. This will imply running the comprehensive and reduced networks in a grid of physical conditions by varying temperature, density, and UV/X-ray fluxes.

Once the reduced network is benchmarked and tested, it will be included in the MOCASSIN-KROME code in collaboration with the postdoc employed on project B2.

2. The chemical model assumes initially that dust grains can be approximated by one-size particles of $0.1\mu$m in diameter and that the dust-to-gas mass ratio is fixed. However, this assumption is completely inappropriate for disc winds. Indeed as explained in detail in project C2 of this proposal, the maximum grain size that can be entrained in the wind at a given radial distance from the star results from the local force balance between the drag force, gravity and the centrifugal force. A further complication is that the underlying distribution of grains is also not constant and varies as a function of disc radius and vertical distance from the midplane, due to the effects of grain growth, fragmentation, settling and drift. A detailed model of the spatially and time- varying grain abundances and size distributions in the wind is however essential for the chemical model, since grains provide the bulk of the opacity in the FUV. The second task of the Postdoc employed for this project will be to include spatially and time-varying grain abundances and size distributions provided by project C2 into the chemical code to properly account for dust opacities in the wind. Also the effects of different dust grain properties on the chemical composition will be explored at this point.

   This second step will be further decomposed into levels of increasing complexity. We will begin with decoupling the time and space evolution of the grains. We will then compare the timescales involved and asses whether the time-evolution of the dust must be treated self-consistently or if we can work with snapshots.

3. Furthermore, it is unclear at this stage if equilibrium chemistry is an appropriate approximation for disc winds. The material flows at a few km/sec and as it moves along the wind streamlines it is subject to changes in density and radiation field. It is likely that time dependent calculations will be necessary for this problem, where the dust properties in the chemical code will be provided by the time dependent calculation of the dust evolution described in C1. This will be the third task of the Postdoc employed for this project.

   After this, the whole team will work together to couple time-dependent gas-grain chemistry and dust evolution. Depending on the level of complexity required part of this final step may be carried out in the second funding period.

   A Postdoc with at least some experience of astrochemistry would be certainly desirable to work on this complex project. The Postdoc will receive scientific support form the PI, but also from the many experienced astrochemists (e.g. Dr Thi and Dr Szucs) at the Centre for Astrochemical Studies led by Prof. Caselli at the MPE.

The final science product will be for the first time a detailed chemical study of a disc wind for one standard case. The lessons learnt will be streamlined and approximated in order to be usable in the parameter space calculations planned for project B1.

**Links to the other projects/ collaborations:** This project relies on inputs from project A2 for the stellar parameters and from project C2 for the dust model in the wind. The reduced network developed here will then be included in the MOCASSIN-KROME code in collaboration with the Postdoc from project B1.

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

**Authors:**

PI: C.P. Dullemond (Heidelberg)
Co-I: W. Kley (Tuebingen), B. Ercolano (LMU)
Collaborations: P. Caselli (MPE), L. Testi (ESO), T. Henning (MPIA)
E. van Dishoeck (Leiden, MPE)

**Requested positions: 1 PhD student**

**Abstract:**
One of the most pressing unsolved problems in the field of planet formation is how Nature overcomes the "radial drift barrier" for dust aggregates in the size range between millimetre and several meters. Observations of TDs may hold the clue. They appear to have strong dust concentrations which suggest dust trapping by local pressure maxima to be the key. It was long suspected that this process plays a critical role in planet formation. TDs may allow us to observe this process in real time. The goal of this project is to do detailed modelling of this process for TDs and compare the results to the observations. This will make a direct link between observations of protoplanetary discs and the process of planet formation.

**Scientific background:**
Planet formation theories suffer from a major problem. The process starts when the dust in the protoplanetary disc around a young star coagulates to become ever bigger dust aggregates. These eventually grow by further mutual collisional mergings to the size of planets. However, as dust aggregates grow from micron size to millimetre-meter size, they start to drift rapidly toward the star. This is a result of the negative radial pressure gradient in the disc (Whipple 1972). The planet formation process is thus aborted when bodies grow to millimetre-meter size. This problem is often called the "radial drift barrier". Already long ago (Whipple 1972; Barge & Sommeria 1995; Klahr & Henning 1997) proposed that local pressure maxima in the disc, if present, would trap dust particles of sufficiently large size and allow particles to grow through the drift barrier.

Recently such dust traps seem to have been discovered observationally in many Type 2 TDs. ALMA observations of these objects show that the dust continuum emission originates from a relatively narrow ring around the star, typically with a radius of several tens of AU. Analysis shows that this dust is likely to be made of millimetre to cm size pebbles. There are strong indications that what we see here are dust trapping pressure-maxima of the kind predicted to play a role in planet formation.

A number of these ring-like TDs in fact are strongly lopsided. The dust appears to be trapped on one side of the star. This appears to confirm an earlier prediction. Li et al. (2000) showed that radial pile-ups of gas can become unstable and produce huge one-sided arc-shaped vortices. It was shown by Regaly et al. (2012) that these vortices have strong resemblance with the observed lopsided arc-shaped TD shapes. Such vortices are known to attract and trap dust (Barge & Sommeria 1995; Klahr & Henning 1997).

TDs are therefore perhaps the best laboratories for observing the processes at work in planet formation, and will likely remain for the forseeable future.

**Scientific objectives:**
The open questions we intend to address in this project are the following. Will dust grain growth be able to break through all the barriers inside the dust trap? Will it form a planet or planets? How much small dust will seep through the dust trap? Will grain growth be efficient enough to keep all dust in large pebbles, so that all the dust remains trapped, or will a substantial fraction of the dust remain in small grains which will get dragged along with the gas into the inner disc region? Can the high-accretion rate, low dust content of the inner disc ("optically thin accretion") be explained? As more and more dust drifts into (and remains trapped inside) the ring/vortex, will the ring/vortex remain stable?

**Tools for the proposed project:**
For this project we will model dust growth and dynamics (and in a simplified way also the continued process of planet formation) in the dust traps thought to be seen in TDs. For this we need first of all a disc model that describes the dust traps well. As a zeroth order approach we will use simple 1-D viscous disc models. For asymmetric discs (with vortices and/or eccentricity) we will use the FARGO-3D hydrodynamics code, which can also do 2-D models. We will implement time-dependent heating-cooling as we did before (e.g. Mueller & Kley 2012, A&A 539, 18; Pohl et al. 2015, MNRAS 453, 1768). We will then implement a time-dependent dust coagulation model (e.g. Birnstiel et al. 2012). Making this viable for 2-D disc models will be a major part of this project. Finally, we will use the RADMC-3D radiative transfer code for making observational predictions from our models.

**Work Plan**
The work plan consists of several sub-projects that aim to answer the questions posed above. In each of them we will not only perform the modeling itself, but also compare their predicted appearances (using RADMC-3D) with the copious ALMA and VLT/SPHERE observations of these objects. The PI and collaborators Prof Henning and Prof van Dishoeck have access to a wealth of new data from these observatories.

1. First we will make 1-D viscous disc evolution models of discs with dead zones, ice lines and/or photoevaporation. The appearance of a massive planet or Brown Dwarf companion, and the gap it creates can be "simulated" by empirical analytic gap structure formulae. We will couple this model to the dust evolution code. Both disc and dust are evolved simultaneously, and we will investigate how the formation of a pressure bump will affect the radial dust distribution and the accretion history of the disc.

2. To study the vortices and/or eccentric gap structures, we will inject the 1-D disc structure (at some time $t$) into the 2-D hydrodynamics code and model how these azimuthal asymmetries develop (collaboration with project D2).

3. We will develop a 2-D version of the dust drift and growth code and let this run on top of the hydrodynamics models, initially without feedback. We will eventually, if time and computational resources permit, model the dust feedback onto the gas in the vortex in 3-D. The dust distributions will be compared with project A1 led by Prof. Testi.

4. We will, in a simplified way, model the subsequent formation of planetary embryos and planets from the dust concentrations in the dust trap, and follow how these will, with their gravity, stir the dust and thereby affect the growth, perhaps inhibiting it, and perhaps leading to observable effects in the dust distribution.

5. By combining our dust physics with chemistry models (in collaboration with Prof. Caselli) we will seek gas-chemical signatures of the dust traps wich we could search for with ALMA.

6. If the gap of the TD is caused by photoevaporation and the gap increases in size (see e.g. Owen, Ercolano et al. (2010, 2011, 2012), we will investigate how the dust and possibly the planet formation happening in the dust trap react to this outside-motion of the trap. Will there by sufficient time to create planetesimals while the trap moves outward? Collaboration with co-I Prof. Ercolano is envisioned here.

**Links to the other projects / collaborations:**
The dust distributions modeled here directly link to project A1. The hydrodynamical models of projects D1 and D2 will be very useful for this project. Photoevaporation models of B1 are important for modeling the time-dependent location of the dust trap (in the photoevaporation scenario).

# Project C2: Gone with the wind: Dust entrainment in photoevaporative winds

**Authors:**

| | |
|---|---|
| PI: | B. Ercolano (LMU) |
| Co-I: | K. Dullemond (Heidelberg) |
| Collaborations: | James Owen (Princeton, USA), P. Caselli (MPE), G. Picogna (LMU) |


**Requested positions: 1 PhD student**

**Abstract:**
The search for the smoking gun of disc dispersal via photoevaporative winds, which destroy discs via the formation of Type 1 TDs, has until now failed to identify suitable tracers. Quantitative spectroscopy of YSOs to search for blue-shifted emission lines produced in the wind relies on an accurate characterisation of the thermochemical properties of the winds. A central ingredients for the chemical calculations is the dust content of the wind as micron sized grains provide the dominant opacity channel in the far-ultraviolet, furthermore small particles are important players in the temperature balance of the gas via the photoelectric process.

We will use realistic radiation-hydrodynamic models of photoevaporative winds coupled to dust evolution models for the underlying grain distribution in the disc, to calculate the dust entrainment in winds to feed to chemical models. The observability of the continuum emission due to the dust grains in winds from edge-on discs, a potential new diagnostic, will be estimated both for Herbig Ae stars and for their fainter T-Tauri counterparts.

**Scientific background:**
The dispersal of protoplanetary discs plays a crucial role in the planet formation process, and it is witnessed by the formation of Type 1 TDs. While photoevaporation from the central star has been proposed as the dominant disc-dispersal mechanism around low-mass stars (e.g. Clarke et 2001), to date only tentative evidence exists of a wind detection, via blue-shifted forbidden line emission of mostly NeII and OI (e.g. Hartigan, Edwards & Ghandour 1995; Alexander 2008; Pascucci & Sterzik 2009; Schisano, Ercolano & Guedel 2010; Ercolano & Owen 2010). These lines can only probe the wind on very local scales and they cannot be inverted to obtain mass loss rates, which are crucial to pin down the driving dispersal wind mechanism (i.e. EUV, FUV or X-ray - or a combination). Different driving mechanism induce more or less vigorous mass loss at different disc radii, which can have dramatic effect on planet formation, both at the times of planetesimal assembly and for the later dynamical evolution of planet(esimal)s (e.g. Ercolano & Rosotti 2015).

Owen, Ercolano & Clarke (2011b) demonstrated that in the case of Herbig Ae/Be stars an EUV-driven wind, the wind selectively entrains grains of different sizes at different radii resulting in a dust population that varies spatially and increases with height above the disc at radii larger than about 10 AU. At near infrared wavelengths this variable grain population produces a 'wingnut' morphology which may have already been observed in the case of PDS 144N (Perrin et al. 2006). The work of Owen et al. (2011b) could not however reproduce the colour gradient of the observations, which show redder emission at larger heights above the disc. Possibly, the problem was due to the fact that the synthetic images were dominated by emission from the smallest grains entrained in the flow. Grain growth, neglected in the Owen et al. (2011b) calculations in the disc is a natural solution to the colour problem, which needs to be taken into account in future simulations.

While it is currently not clear if the PDS 144N observation can be explained by dust entrainment in a photoevaporative wind, the work of Owen, Ercolano & Clarke (2011b) has clearly demonstrated that a significant amount of small grains (which dominate the opacity in the FUV) do populate disc winds, hence playing an important part in the chemistry there and at the base of the flow. The Owen, Ercolano & Clarke (2011b) calculation are limited to the EUV-case only and do not include dust-evolution in the underlying disc. In this project we aim to determine the dust content of photoevaporative winds for the EUV and X-ray case for a range of stellar, disc and wind parameters, using realistic descriptions for grain growth in the underlying disc.

The main science product of this project, i.e. the grain distributions, is needed by project B1, however as a by-product we will also use the results to predict the observational appearance of the wind in infrared continuum for the various cases. In the case of Herbig Ae stars these winds may be observable for edge-on discs as discussed in Owen et al. (2011b) and may provide an interesting wind diagnostic.

**Scientific objectives:**

1. Build a dust model for photoevaporative winds to be used in chemical calculations.
2. Estimate the observability and observation characteristics of the dust phase in photoevaporative winds.

**Strategy of the proposed project:**
For this project we will need the following tools:

1. Photoevaporative wind solutions for EUV and X-ray photoevaporated winds for T-Tauri and Herbig stars (the latter only for the EUV case)
2. Parameterised dust growth models (e.g. Birnstiel, Klahr & Ercolano, 2012) and, successively, dust evolution results from project C1.
3. A 3D radiative transfer code to post-postprocess the wind models with the calculated grain populations. We will make use of the RadMC code developed and maintained by Prof. Dullemond.

The student will start by producing wind solution for the EUV case from the work of Font et al. (2004), which may be applicable to Herbig stars. She/he will then proceed to calculate the dust distribution in the wind, under simplifying assumptions for the underlying dust distributions as in Owen et al (2011b). In brief, streamlines from the base of the flow to the edge of the grid will be computed and along each of them, the force balance between the drag force, gravity and the centrifugal force will be calculated. A positive net force on a grain along the streamline will indicate that the grain is entrained. This first models will be benchmarked against the solutions of Owen et al. (2011b). The student will then be in a position to significantly improve on this work by considering grain growth and settling in the disc, first of all using the simple prescriptions or Birnstiel, Klahr & Ercolano (2012). At a later stage the models will use the results from the calculations of dust evolution carried out in project C1. For the X-ray case the student will at first make use of the existing wind solutions of Owen et al. (2010, 2011, 2012).This systematic approach will allow us to distinguish amongst the various effects and will also allow us to understand wether a more efficient, simplified approach may then be used.

The new wind models for the X-ray case are already being calculated by Dr Picogna, who is employed to do the preparatory work from project B1, and will be available to the student. She/he will then be able to apply the constructed and benchmarked machinery to a wide parameter space, performing radiative transfer calculations of the obtained structures to compare with available observations or to make observability predictions which may guide future observing proposals. We will join forces with expert collaborators on scattered light observations (e.g. Prof. Henning) to plan new proposals, however we note that failure to obtain new observations does not preclude the main aims of this projects to be achieved. The most important science product from this project is in fact, the grain models developed for the X-ray driven wind, which are needed by project B1 for the chemical calculations. This is crucial as the dust grains are not equally distributed in the wind (see e.g. Owen, Ercolano & Clarke, 2012) and affect the chemistry of the wind differently in different part. We stress that a simple estimate from a non-detection is not sufficient to rule out the relevance of grains on the chemical calculations.

If time allows, the student will collaborate with Dr Picogna (B1) to produce full hydrodynamical simulations of disc winds, where the component in the disc and wind is treated as particles (e.g. Picogna & Kley 2016). These calculations, which are computationally expensive will be seful as a comparison to the simpler methods previously employed by the student in the project.

**Links to the other projects / collaborations:** The project will use the wind models calculated in project B1 and then feed back the dust model to the same project (B1) and to the reduced chemical network tests of project B2. Dust evolution calculations from C1 will also be used. Observational constraints will be obtained in collaboration with experts working on project A1 and stellar properties to guide the models from project A2.

# Project D1: TDs and planetary systems

**Authors:**
PI: W. Kley (Tübingen)
Co-I: C.P. Dullemond (Heidelberg)
Collaborations: L. Testi (ESO), T. Henning (MPIA), E. van Dishoeck (Leiden, MPE)

**Requested position: 1 Postdoc**

**Abstract:**
As described in the general introduction, transitional discs (TDs) 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. The second, Type 2 variety, of these discs contain larger inner holes with significant gas accretion from the inner region present. It has been suggested that for Type 2 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 dust particles, planets, radiation transport and irradiation from the central star.

**Scientific background:**
Observationally, TDs are characterised by a lack of flux in the few $\mu$-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 1 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 (Varniere 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, and indeed Zhu et al. (2011) and Dodson-Robinson & 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 TDs, 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 short-comings. The simulations treat the disc in the isothermal approximation, 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.

**Scientific objectives:** In this project we plan to improve significantly on existing models for Type 2 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.

**Strategy of the proposed project:**
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, building up on complexity, while proving a solid groundwork to understand the new results:

1. To connect to existing simulations of Zhu et al. (2011) and our own (Müller & 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 & Kley (2012).

2. Dust particles will then be added to these models whose motion (in particular the important stopping-time) 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 & Kley (2016) and calculate emission maps (using the RADMC-3D code, see **C1** and **D2**) that will then be directly compared to observations (**A1**). We note that the full treatment of dust grains as discrete particles is a relatively new technique, for which our group has performed some of the pioneering work.

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. For these 3D simulations we plan to study the influence of inclined planet(s) which relates closely to project **D2**. Our 3D simulations will push significantly past the state-of-the-art of hydrodynamical modeling of Type 2 TDs.

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. This is basically uncharted territory, but an urgent and necessary step, as our previous work (Bitsch et al. 2013ab, 2014ab) has shown that forcing an isothermal approach may lead to large errors in the description of planet-disc interactions.

**Personnel:** For the project 1 postdoc position is requested. The planned work, including 2D and 3D radiation hydrodynamical simulations, the dust motion and the generation of images is very demanding and requires a more experienced young researcher.

**Links to the other projects / collaborations:** There will be close collaboration with project **D2** in Heidelberg concerning the 3D evolution of non-axisymmetric discs, and with **C1** on non-axisymmetric disc features. The radiative transfer modelling will be done in close collaboration the Heidelberg team (C. Dullemond). For direct comparison with the observations a close collaboration with the Garching team (L. Testi), as well as with Prof. Henning (MPIA) and Prof. van Dishoeck (Leiden, MPE) is anticipated.

# Project D2: Origin of complex non-axisymmetric structures in TDs

**Authors:**

| | |
|---|---|
| PI: | C.P. Dullemond (Heidelberg) |
| Co-I: | W. Kley (Tübingen) |
| Collaborations: | L. Testi (ESO), Ercolano (USM) , T. Henning (MPIA), E. van Dishoeck (Leiden, MPE) |


**Requested positions: 1 postdoc**

**Abstract:**
Type 2 TDs have recently been shown to display spectacular structures such as large scale spirals, blobs, tilts etc. These features indicate that highly dynamic processes are going on in these discs, allowing us to test our understanding of the physics of protoplanetary discs. This project aims to understand these structures in terms of dynamic models of discs.

**Scientific background:**
With the spectacular new capabilities of observatories in the millimetre wavelength range (ALMA) and at optical wavelengths (Subaru and VLT coronographic imagers, most recently: VLT-SPHERE), protoplanetary discs are found to be much more complex than previously thought. Until only a few years ago observations of protoplanetary discs were consistent with the idea of them being axi-symmetric rotating structures around young stars.

Recent observations have now shown this picture to be false, in particular for Type 2 TDs. Many such discs, while remarkable in their own right due to their large inner holes (see project D1), are even more remarkable due to their often-present strong deviations from axisymmetry. At millimetre wavelengths, spatially resolved with ALMA, all TDs show a strong dust emission ring just beyond the inner hole. Several of them, in particular the sources HD 142527 and Oph IRS 48, show this ring to be strongly lopsided: one side being clearly much brighter than the other side (Casassus et al. 2013; Van der Marel et al. 2013). These appear to be vortices created by the Rossby wave instability (Regaly et al. 2012). This raises the exciting possibility that these are *dust-trapping vortices*, predicted to play an important role in planet formation (Barge & Sommeria 1995; Klahr & Henning 1997).

At optical and near infrared wavelengths many of these sources show another remarkable and unexpected feature: grand design spiral waves (e.g. the sources HD 135344b, MWC 758, HD 100453). While $m = 1$ spiral waves were expected as a result of newborn planets embedded in these discs, the spirals observed in many Type 2 TDs are symmetric $m = 2$ modes, making them look like the galaxy M51. The origin of these spirals is still hotly debated and planetary/stellar companions and gravitational instabilities are often suggested to be at their origin, as is residual infall into the disc. Recently an even more bizarre and intriguing scenario was proposed: The bright ring of scattered light (the illuminated inner rim of the outer disc as seen with the Subaru and VLT telescopes) of HD 142527 has two conspicuous dark spots on almost opposite sides. Marino et al. (2015) were able to show with 3-D radiative transfer modeling that these dark spots are most likely the shadows cast by an inclined small inner disc. If this scenario is confirmed, HD 142527 (and possibly other TDs) is an "inclined disc inside a disc" (a warped disc). According to Montesinos et al. (2016) these two shadows on opposite sides of the bright rim may even be the origin of the $m = 2$ spiral waves, caused by the brief loss of pressure in these shadows.

But how can the inner disc have a different rotation axis as the outer one? Is this a result of an inclined planet or brown dwarf orbiting inside the gap? Or is this due to late accretion of different angular momentum molecular cloud material? Or could the Kozai-mechanism caused by a companion at large radii cause this?

**Scientific objectives:** This project aims to study the dynamics of non-axisymmetric and/or non-coplanar transition inner-and-outer discs with the goal of trying to learn from these spectacular "disk dynamics laboratories" of Nature. We expect that we will be forced to include new elements to our standard models (e.g. planets or brown dwarf companions on eccentric or even inclined orbits; external secondary gas infall; complex dust-gas dynamics; photoevaporation of warped discs etc), which would thus improve our understanding of the workings of protoplanetary discs and planet formation.

**Tools for the proposed project:**
For this project we will require three main tools. First: A 3-D hydrodynamics modeling code that can deal with complex dynamics without any symmetry axis, yet can deal also with the large radial dynamic range (from a few AU to a few 100 AU) required for these objects. The PLUTO code is our current choice, since we have our own experience with this code. Second: A 3-D radiation-hydrodynamics module on top of the 3-D hydrodynamics code, that can deal with irradiation. The PIs of this proposal are the co-authors of such a module (Kuiper et al. 2010). Finally: A powerful 3-D diagnostic radiative transfer code to allow us to make predictions for the observational appearance of the 3-D model results. We have in-house software: RADMC-3D

**Work Pan**
The work plan consists of several sub-projects that aim to explain the non-axisymmetric features mentioned above. In each of these sub-projects we will not only do the (radiation-)hydrodynamic modeling, but also compare their predicted appearances (using RADMC-3D) with the copious ALMA and VLT/SPHERE observations of these objects.

1. We will perform 3-D hydrodynamics (and possibly radiation-hydrodynamics) simulations of the following scenarios in order to test if they can explain (1) the huge gap between the inner and outer discs and (2) the suspected inclination of the inner disc in some of these sources:

   (a) A massive *inclined* planet or brown dwarf companion inside the disc causing the warp. Strong collaboration with project D1 is envisioned here.

   (b) A secondary outer disc accreted from a nearby cloud filament, causing a randomly inclined outer disc.

   (c) Photoevaporation of a warped disc, perhaps being responsible for the huge gap (as UV and X-ray photons can reach the intermediate disc regions more easily for warped discs). Strong collaboration with project B1 is envisioned here.

   In the above models: what is the connection between the inner and outer disk?

2. We will perform 2-D and 3-D radiation-hydrodynamic simulations of the following scenarios to see if they explain the production of $m = 2$ spirals:

   (a) Shadow-spots by the inclined inner disc triggering spirals

   (b) Spirals triggered by a companion and/or gravitational instability

   New compared to earlier work will be the use of our powerful radiation-hydrodynamics module, which is critical to get the thermodynamics (and thereby the crux of these models) right.

3. Revisit the Rossby-wave instability origin of the observed vortices, comparing the different scenarios of inner hole formation against each other (planets, massive companion, inclined companion, photoevaporation): do they all predict these vortices? And are vortices and spirals predicted simultaneously or mutually exclusively? Project C1.

**Links to the other projects / collaborations:**
The team (Dullemond, Kley, Testi, Ercolano) have all the necessary expertise to carry out the modeling and the comparison to observations. In addition collaboration with the groups of Th. Henning (MPIA), E. van Dishoeck (MPE/Leiden), M. Benisty (Grenoble) and C. Dominik (Amsterdam) is envisioned for the comparison to observational data with ALMA and SPHERE.

# References


[1] Alexander, R. D., Clarke, C. J., & Pringle, J. E. 2006, *Monthly Notices Roy. Astr. Soc.*, 369, 216

[2] Alexander, R. D. 2008, *Monthly Notices Roy. Astr. Soc.*, 391, L64

[3] Alexander, R. D., & Pascucci, I. 2012, *Monthly Notices Roy. Astr. Soc.*, 422, L82

[4] Aresu, G., Meijerink, R., Kamp, I., et al. 2012, *Astron. & Astrophys.*, 547, A69

[5] Banzatti, A., Testi, L., Isella, A., et al. 2011, *Astron. & Astrophys.*, 525, A12

[6] Barge, P., & Sommeria, J. 1995, *Astron. & Astrophys.*, 295, L1

[7] Benisty, M., Juhasz, A., Boccaletti, A., et al. 2015, *Astron. & Astrophys.*, 578, L6

[8] Birnstiel, T., Dullemond, C. P., & Brauer, F. 2010, *Astron. & Astrophys.*, 513, A79

[9] Birnstiel, T., Klahr, H., & Ercolano, B. 2012, *Astron. & Astrophys.*, 539, A148

[10] Birnstiel, T., Andrews, S. M., & Ercolano, B. 2012, *Astron. & Astrophys.*, 544, A79

[11] Bitsch, B., Boley, A., & Kley, W. 2013a, *Astron. & Astrophys.*, 550, A52

[12] Bitsch, B., Crida, A., Morbidelli, A., Kley, W., & Dobbs-Dixon, I. 2013b, *Astron. & Astrophys.*, 549, A124

[13] Bitsch, B., Morbidelli, A., Lega, E., Kretke, K., & Crida, A. 2014a, *Astron. & Astrophys.*, 570, A75

[14] Bitsch, B., Morbidelli, A., Lega, E., & Crida, A. 2014b, *Astron. & Astrophys.*, 564, A135

[15] Brauer, F., Dullemond, C. P., & Henning, T. 2008, *Astron. & Astrophys.*, 480, 859

[16] Brown, J. M., Pontoppidan, K. M., van Dishoeck, E. F., et al. 2013, *Astrophysical J.*, 770, 94

[17] Bruderer, S., Harsono, D., & van Dishoeck, E. F. 2015, *Astron. & Astrophys.*, 575, A94

[18] Calvet, N., D'Alessio, P., Hartmann, L., et al. 2002, *Astrophysical J.*, 568, 1008

[19] Cassan, A., Kubas, D., Beaulieu, J.-P., et al. 2012, *Nature*, 481, 167

[20] Casassus, S., van der Plas, G., M, S. P., et al. 2013, *Nature*, 493, 191

[21] Chatterjee, S., & Tan, J. C. 2014, *Astrophysical J.*, 780, 53

[22] Chatterjee, S., & Tan, J. C. 2015, *Astrophysical J. Lett.*, 798, L32

[23] Clarke, C. J., Gendrin, A., & Sotomayor, M. 2001, *Monthly Notices Roy. Astr. Soc.*, 328, 485

[24] D'Alessio, P., Hartmann, L., Calvet, N., et al. 2005, *Astrophysical J.*, 621, 461

[25] Dodson-Robinson, S. E., & Salyk, C. 2011, *Astrophysical J.*, 738, 131

[26] Douglas, T. A., Caselli, P., Ilee, J. D., et al. 2013, *Monthly Notices Roy. Astr. Soc.*, 433, 2064

[27] Drążkowska, J., & Dullemond, C. P. 2014, *Astron. & Astrophys.*, 572, A78

[28] Drake, J. J., Ercolano, B., Flaccomio, E., & Micela, G. 2009, *Astrophysical J. Lett.*, 699, L35

[29] Ercolano, B., Barlow, M. J., Storey, P. J., & Liu, X.-W. 2003, *Monthly Notices Roy. Astr. Soc.*, 340, 1136

[30] Ercolano, B., Barlow, M. J., & Storey, P. J. 2005, *Monthly Notices Roy. Astr. Soc.*, 362, 1038

[31] Ercolano, B., Drake, J. J., Raymond, J. C., & Clarke, C. C. 2008a, *Astrophysical J.*, 688, 398

[32] Ercolano, B., Young, P. R., Drake, J. J., & Raymond, J. C. 2008b, *Astrophysical J. Suppl.*], 175, 534

[33] Ercolano, B., Clarke, C. J., & Drake, J. J. 2009, *Astrophysical J.*, 699, 1639

[34] Ercolano, B., & Owen, J. E. 2010, *Monthly Notices Roy. Astr. Soc.*, 406, 1553

[35] Ercolano, B., Clarke, C. J., & Hall, A. C. 2011, *Monthly Notices Roy. Astr. Soc.*, 410, 671

[36] Ercolano, B., & Glassgold, A. E. 2013, *Monthly Notices Roy. Astr. Soc.*, 436, 3446

[37] Ercolano, B., Mayr, D., Owen, J. E., Rosotti, G., & Manara, C. F. 2014, *Monthly Notices Roy. Astr. Soc.*, 439, 256

[38] Ercolano, B., Koepferl, C., Owen, J., & Robitaille, T. 2015, *Monthly Notices Roy. Astr. Soc.*, 452, 3689

[39] Ercolano, B., & Rosotti, G. 2015, *Monthly Notices Roy. Astr. Soc.*, 450, 3008

[40] Evans, M. G., Ilee, J. D., Boley, A. C., et al. 2015, *Monthly Notices Roy. Astr. Soc.*, 453, 1147

[41] Font, A. S., McCarthy, I. G., Johnstone, D., & Ballantyne, D. R. 2004, *Astrophysical J.*, 607, 890

[42] Gorti, U., Dullemond, C. P., & Hollenbach, D. 2009, *Astrophysical J.*, 705, 1237

[43] Grassi, T., Bovino, S., Schleicher, D. R. G., et al. 2014, *Monthly Notices Roy. Astr. Soc.*, 439, 2386

[44] Guidi, G., Scannapieco, C., & Walcher, C. J. 2015, *Monthly Notices Roy. Astr. Soc.*, 454, 2381

[45] Guidi, G., Tazzari, M., Testi, L., et al. 2016, *Astron. & Astrophys.*, 588, A112

[46] Hartigan, P., Edwards, S., & Ghandour, L. 1995, *Astrophysical J.*, 452, 736

[47] Hartmann, L., Calvet, N., Gullbring, E., & D'Alessio, P. 1998, *Astrophysical J.*, 495, 385

[48] Hubber, D. A., Ercolano, B., & Dale, J. 2016, *Monthly Notices Roy. Astr. Soc.*, 456, 756

[49] Ilee, J. D., Boley, A. C., Caselli, P., et al. 2011, *Monthly Notices Roy. Astr. Soc.*, 417, 2950

[50] Ivlev, A. V., Padovani, M., Galli, D., & Caselli, P. 2015, *Astrophysical J.*, 812, 135

[51] Kataoka, A., Muto, T., Momose, M., et al. 2015, *Astrophysical J.*, 809, 78

[52] Kenyon, S. J., & Hartmann, L. 1995, *Astrophysical J. Suppl.*], 101, 117

[53] Keto, E., Rawlings, J., & Caselli, P. 2014, *Monthly Notices Roy. Astr. Soc.*, 440, 2616

[54] Klaassen, P. D., Juhasz, A., Mathews, G. S., et al. 2013, *Astron. & Astrophys.*, 555, A73

[55] Klaassen, P. D., Mottram, J. C., Maud, L. T., & Juhasz, A. 2016, *Monthly Notices Roy. Astr. Soc.*

[56] Klahr, H. H., & Henning, T. 1997, *Icarus*, 128, 213

[57] Kley, W., & Crida, A. 2008, *Astron. & Astrophys.*, 487, L9

[58] Kley, W., Bitsch, B., & Klahr, H. 2009, *Astron. & Astrophys.*, 506, 971

[59] Kley, W., & Nelson, R. P. 2012, *ARAA*, 50, 211

[60] Kley, W., & Haghighipour, N. 2014, *Astron. & Astrophys.*, 564, A72

[61] Koepferl, C. M., Ercolano, B., Dale, J., et al. 2013, *Monthly Notices Roy. Astr. Soc.*, 428, 3327

[62] Kuiper, R., Klahr, H., Dullemond, C., Kley, W., & Henning, T. 2010, *Astron. & Astrophys.*, 511, A81

[63] Li, H., Finn, J. M., Lovelace, R. V. E., & Colgate, S. A. 2000, *Astrophysical J.*, 533, 1023

[64] Luhman, K. L., Allen, P. R., Espaillat, C., Hartmann, L., & Calvet, N. 2010, *Astrophysical J. Suppl.*], 186, 111

[65] Lynden-Bell, D., & Pringle, J. E. 1974, *Monthly Notices Roy. Astr. Soc.*, 168, 603

[66] Manara, C. F., Robberto, M., Da Rio, N., et al. 2012, *Astrophysical J.*, 755, 154

[67] Manara, C. F., Beccari, G., Da Rio, N., et al. 2013, *Astron. & Astrophys.*, 558, A114

[68] Manara, C. F., & Testi, L. 2014, *Astroph. & Space Science*, 354, 35

[69] Manara, C. F., Beccari, G., Da Rio, N., et al. 2013, *Astron. & Astrophys.*, 558, A114

[70] Manara, C. F., & Testi, L. 2014, *Astroph. & Space Science*, 354, 35

[71] Manara, C. F., Fedele, D., Herczeg, G. J., & Teixeira, P. S. 2016, *Astron. & Astrophys.*, 585, A136

[72] Marino, S., Casassus, S., Perez, S., et al. 2015a, *Astrophysical J.*, 813, 76

[73] Marino, S., Perez, S., & Casassus, S. 2015b, *Astrophysical J. Lett.*, 798, L44

[74] Meijerink, R., Aresu, G., Kamp, I., et al. 2012, *Astron. & Astrophys.*, 547, A68

[75] Montesinos, M., Perez, S., Casassus, S., et al. 2016, arXiv:1601.07912

[76] Mullally, F., Coughlin, J. L., Thompson, S. E., et al. 2015, *Astrophysical J. Suppl.*], 217, 31

[77] Müller, T. W. A., & Kley, W. 2012, *Astron. & Astrophys.*, 539, A18

[78] Müller, T. W. A., & Kley, W. 2013, *Astron. & Astrophys.*, 560, A40

[79] Muto, T., Grady, C. A., Hashimoto, J., et al. 2012, *Astrophysical J. Lett.*, 748, L22

[80] Owen, J. E., Ercolano, B., Clarke, C. J., & Alexander, R. D. 2010, *Monthly Notices Roy. Astr. Soc.*, 401, 1415

[81] Owen, J. E., Ercolano, B., & Clarke, C. J. 2011, *Monthly Notices Roy. Astr. Soc.*, 412, 13

[82] Owen, J. E., Ercolano, B., & Clarke, C. J. 2011b, *Monthly Notices Roy. Astr. Soc.*, 411, 1104

[83] Owen, J. E., Clarke, C. J., & Ercolano, B. 2012, *Monthly Notices Roy. Astr. Soc.*, 422, 1880

[84] Owen, J. E., Scaife, A. M. M., & Ercolano, B. 2013, *Monthly Notices Roy. Astr. Soc.*, 434, 3378

[85] Pascucci, I., Hollenbach, D., Najita, J., et al. 2007, *Astrophysical J.*, 663, 383

[86] Pascucci, I., & Sterzik, M. 2009, *Astrophysical J.*, 702, 724

[87] Perrin, M. D., Duchêne, G., Kalas, P., & Graham, J. R. 2006, *Astrophysical J.*, 645, 1272

[88] Picogna, G., & Kley, W. 2015, *Astron. & Astrophys.*, 584, A110

[89] Pinilla, P., Benisty, M., Birnstiel, T., et al. 2014, *Astron. & Astrophys.*, 564, A51

[90] Pohl, A., Pinilla, P., Benisty, M., et al. 2015, *Monthly Notices Roy. Astr. Soc.*, 453, 1768

[91] Pontoppidan, K. M., Blake, G. A., & Smette, A. 2011, *Astrophysical J.*, 733, 84

[92] Preibisch et al. 2005, ApJS 160,401

[93] Preibisch et al. 2011, ApJS 194, 10

[94] Preibisch, T., Roccatagliata, V., Gaczkowski, B., & Ratzka, T. 2012, *Astron. & Astrophys.*, 541, A132

[95] Preibisch, T., Zeidler, P., Ratzka, T., Roccatagliata, V., & Petr-Gotzens, M. G. 2014, *Astron. & Astrophys.*, 572, A116

[96] Ramsey, J. P., & Dullemond, C. P. 2015, *Astron. & Astrophys.*, 574, A81

[97] Regály, Z., Juhász, A., Sándor, Z., & Dullemond, C. P. 2012, *Monthly Notices Roy. Astr. Soc.*, 419, 1701

[98] Rice, W. K. M., Armitage, P. J., Wood, K., & Lodato, G. 2006, *Monthly Notices Roy. Astr. Soc.*, 373, 1619

[99] Ricci, L., Testi, L., Natta, A., et al. 2010a, *Astron. & Astrophys.*, 512, A15

[100] Ricci, L., Testi, L., Natta, A., & Brooks, K. J. 2010b, *Astron. & Astrophys.*, 521, A66

[101] Rosotti, G. P., Ercolano, B., Owen, J. E., & Armitage, P. J. 2013, *Monthly Notices Roy. Astr. Soc.*, 430, 1392

[102] Rosotti, G. P., Ercolano, B., & Owen, J. E. 2015, *Monthly Notices Roy. Astr. Soc.*, 454, 2173

[103] Schisano, E., Ercolano, B., Guedel, M. 2010, *Monthly Notices Roy. Astr. Soc.*, 401, 1636

[104] Stehle, R., & Spruit, H. C. 2001, *Monthly Notices Roy. Astr. Soc.*, 323, 587

[105] Tazzari, M., Testi, L., Ercolano, B., et al. 2016, *Astron. & Astrophys.*, 588, A53

[106] Testi, L., Natta, A., Shepherd, D. S., & Wilner, D. J. 2003, *Astron. & Astrophys.*, 403, 323

[107] Testi, L., Birnstiel, T., Ricci, L., et al. 2014, Protostars and Planets VI, 339

[108] Thi, W. F., Ménard, F., Meeus, G., et al. 2013, *Astron. & Astrophys.*, 557, A111

[109] Trotta, F., Testi, L., Natta, A., Isella, A., & Ricci, L. 2013, *Astron. & Astrophys.*, 558, A64

[110] van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2013, Science, 340, 1199

[111] van der Marel, N., Verhaar, B. W., van Terwisga, S., et al. 2016, arXiv:1603.07255

[112] Varnière, P., Blackman, E. G., Frank, A., & Quillen, A. C. 2006, *Astrophysical J.*, 640, 1110

[113] Wagner, K., Apai, D., Kasper, M., & Robberto, M. 2015, *Astrophysical J. Lett.*, 813, L2

[114] Whipple, F. L., 1972, From Plasma to Planet, 211

[115] Woitke, P., Pinte, C., Tilling, I., et al. 2010, *Monthly Notices Roy. Astr. Soc.*, 405, L26

[116] Zhao, B., Caselli, P., Li, Z.-Y., et al. 2016, arXiv:1602.02729

[117] Zhu, Z., Nelson, R. P., Hartmann, L., Espaillat, C., & Calvet, N. 2011, *Astrophysical J.*, 729, 47

## Publication List for the Subprojects

**Project A1** PI: L. Testi Co-PI: B. Ercolano, T. Preibisch

Testi, L. et al. 2014 *Dust Evolution in Protoplanetary Disks* Protostars and Planets VI, 339

Ricci, L.; Testi, L.; Natta, A.; Neri, R.; Cabrit, S.; Herczeg, G. J. 2010 *Dust properties of protoplanetary disks in the Taurus-Auriga star forming region from millimeter wavelengths* 2010 A&A 512, 15

Isella, A.; Testi, L.; Natta, A. 2006 *Large dust grains in the inner region of circumstellar disks* A&A 451, 951

Testi, L.; Natta, A.; Shepherd, D. S.; Wilner, D. J. 2003 *Large grains in the disk of CQ Tau* A&A 403, 323

Ercolano, B.; Owen, J. E. 2010 *Theoretical spectra of photoevaporating protoplanetary discs: an atlas of atomic and low-ionization emission lines* MNRAS 406, 1553

Birnstiel, T.; Andrews, S. M.; Ercolano, B. 2012 *Can grain growth explain transition disks* A&A 544, 79

Ercolano, B.; Koepferl, C.; Owen, J.; Robitaille, T. 2015 *Far-infrared signatures and inner hole sizes of protoplanetary discs undergoing inside-out dust dispersal* MNRAS 452, 3689

S. Kraus, Th. Preibisch, K. Ohnaka, 2008 *Detection of an Inner Gaseous Component in a Herbig Be Star Accretion Disk: Near- and Mid-Infrared Spectrointerferometry and Radiative Transfer modeling of MWC 147* ApJ 676, 490Ð508

Th. Preibisch et al. 2011 *Near-Infrared properties of the X-ray emitting young stellar objects in the Carina Nebula* ApJS, 194, 10

B. Gaczkowski, Th. Preibisch, Th. Ratzka, V. Roccatagliata, H. Ohlendorf, H. Zinnecker 2012 *Herschel far-infrared observations of the Carina Nebula complex. II. The embedded young stellar and protostellar population* A&A 541, A132

**Project A2** PI: T. Preibisch Co-PI: B. Ercolano, L. Testi

Th. Preibisch, 2004, *X-ray Activity and Accretion in Young Stellar Objects*, AspS 292, 631Ð641

Th. Preibisch, et al. 2005 *The Origin of T Tauri X-ray Emission: New Insights from the Chandra Orion Ultradeep Project* ApJS 160, 401Ð422

Th. Preibisch, E.D. Feigelson, 2005 *The Evolution of X-Ray Emission in Young Stars* ApJS 160, 390Ð400

Th. Preibisch et al. 2011 *Near-Infrared properties of the X-ray emitting young stellar objects in the Carina Nebula* ApJS, 194, 10

Ercolano, B.; Mayr, D.; Owen, J. E.; Rosotti, G.; Manara, C. F. 2014 *The dotM* $- M_*$ *relation of pre-main-sequence stars: a consequence of X-ray driven disc evolution* MNRAS 439, 256

Drake, J. J.; Ercolano, B.; Flaccomio, E.; Micela, G. 2009 *X-ray Photoevaporation-Starved T Tauri Accretion* ApJ 699, 35

Ercolano, B.; Clarke, C. J.; Drake, J. J. 2009 *X-Ray Irradiated Protoplanetary Disk Atmospheres. II. Predictions from Models in Hydrostatic Equilibrium* ApJ 699, 1639

Manara, C. F.; Testi, L.; Natta, A.; Rosotti, G.; Benisty, M.; Ercolano, B.; Ricci, 2014 L. *Gas content of transitional disks: a VLT/X-Shooter study of accretion and winds* A&A 568, 18

Manara, C. F.; Testi, L.; Natta, A.; AlcalĞ, J. M. 2015 *X-Shooter study of accretion in $\rho$-Ophiucus: very low-mass stars and brown dwarfs* A&A 579,66

Manara, C. F.; Testi, L.; Natta, A.; Rosotti, G.; Benisty, M.; Ercolano, B.; Ricci, L. 2014 *Gas content of transitional disks: a VLT/X-Shooter study of accretion and winds* A&A 568, 18

**Project B1** PI: B. Ercolano Co-PI: P. Caselli, C. P. Dullemond, W. Kley

Ercolano, B.; Owen, J. E. 2010 *Theoretical spectra of photoevaporating protoplanetary discs: an atlas of atomic and low-ionization emission lines* MNRAS 406, 1553

Owen, J. E.; Ercolano, B.; Clarke, C. J.; Alexander, R. D. 2010 *Radiation-hydrodynamic models of X-ray and EUV photoevaporating protoplanetary discs* MNRAS 401, 1415

Schisano, E.; Ercolano, B.; G§del, M. 2010 *Effects of X-ray irradiation and disc flaring on the [NeII] 12.8 $\mu$m emission from young stellar objects* MNRAS 401, 1636

Owen, J. E.; Clarke, C. J.; Ercolano, B. 2012 *On the theory of disc photoevaporation* MNRAS 422, 1880

Sipila, O., Caselli, P., Harju, J. 2015 *Benchmarking spin-state chemistry in starless core models* A&A,578, 55

Caselli, P., & Ceccarelli, C. 2012 *Our astrochemical heritage* A&ARv, 20, 56z

Visser, R., van Dishoeck, E.F., Doty, S.D. and Dullemond, C.P. 2009 *The chemical history of molecules in circumstellar disks. I. Ices*,A&A 495, 881

Rosenfeld, K.A., Qi, C., Andrews, S.M., Wilner, D.J., Corder, S.A., Dullemond, C.P., Lin, S., Hughers, A.M., D'Alessio, P., Ho, P.T.P. 2012 *Kinematics of the CO Gas in the Inner Regions of the TW Hya Disk*, ApJ, 757, 129

Kolb, S. M., Stute, M., Kley, W. & Mignone, A. (2013) *Radiation hydrodynamics integrated in the PLUTO code* A&A, 559, A80

Müller, T. & Kley, W. (2013) *Modelling accretion in transitional disks* A&A 560, A40

**Project B2** PI: P. Caselli Co-PI: B. Ercolano

Evans, M. G. et al. 2015 *Gravitational instabilities in a protosolar-like disc I: dynamics and chemistry* MRAS 453, 1147

Sipila, O., Caselli, P., Harju, J. 2015 *Benchmarking spin-state chemistry in starless core models* A&A,578, 55

Caselli, P., & Ceccarelli, C. 2012 *Our astrochemical heritage* A&ARv, 20, 56

P., Keto, E., Bergin, E. A., 2012 *First Detection of Water Vapor in a Pre-stellar Core* ApJ, 759, L37

Ilee, J. D., Boley, A. C., Caselli, P., et al. 2011 *Chemistry in a gravitationally unstable protoplanetary disc* MNRAS, 417, 2950

Ercolano, B.; Glassgold, A. E. 2013 *X-ray ionization rates in protoplanetary discs* MNRAS 436, 3446

Ercolano, B.; Owen, J. E. 2010 *Theoretical spectra of photoevaporating protoplanetary discs: an atlas of atomic and low-ionization emission lines* MNRAS 406, 1553

Ercolano, B.; Young, P. R.; Drake, J. J.; Raymond, J. C. 2008 *X-Ray Enabled MOCASSIN: A Three-dimensional Code for Photoionized Media* ApJS 165, 534

Ercolano, B.; Barlow, M. J.; Storey, P. J. 2005 *The dusty MOCASSIN: fully self-consistent 3D photoionization and dust radiative transfer models* MNRAS 362, 1038

Ercolano, B.; Barlow, M. J.; Storey, P. J.; Liu, X.-W. 2003 *MOCASSIN: a fully three-dimensional Monte Carlo photoionization code* MNRAS 340 1136

**Project C1** PI: C. P. Dullemond Co-PI: W. Kley, B. Ercolano

Birnstiel, T., Dullemond, C.P. & Brauer, F. 2010 *Gas and dust evolution in protoplanetary disks* A&A 513, 79

Pinilla, P., Birnstiel, T., Ricci, L., Dullemond, C.P., Uribe, A.L., Testi, L., Natta, A. 2012 *Trapping dust particles in the outer regions of protoplanetary disks* A&A 538, 114

van der Marel, N., et al. 2013 *A Major Asymmetric Dust Trap in a Transition Disk* Science, 340, 1199

Ataiee, S., Pinilla, P., Zsom, A., Dullemond, C.P., Dominik, C., Ghanbari, J., 2013 *Asymmetric transition discs: Vorticity or eccentricity?* A&A, 553, L3

Kolb, S. M., Stute, M., Kley, W. & Mignone, A. (2013) *Radiation hydrodynamics integrated in the PLUTO code* A&A 559, A80

Kuiper, R., Klahr, H., Dullemond, C., Kley, W. & Henning, T. (2010) *Fast and accurate frequency-dependent radiation transport for hydrodynamics simulations in massive star formation* A&A 511, A81

Müller, T. Kley, W. & Meru, F. (2012) *Treating gravity in thin-disk simulations* A&A 541, A123

Birnstiel, T.; Andrews, S. M.; Ercolano, B. 2012 *Can grain growth explain transition disks?* A&A 544, 79

Birnstiel, T.; Klahr, H.; Ercolano, B. 2012 *A simple model for the evolution of the dust population in protoplanetary disks* A&A 539, 148

**Project C2** PI: B. Ercolano Co-PI: C. P. Dullemond

Owen, J. E.; Ercolano, B.; Clarke, C. J. 2011 *Protoplanetary disc evolution and dispersal: the implications of X-ray photoevaporation* MNRAS 412,13

Owen, J. E.; Ercolano, B.; Clarke, C. J. 2012 *The imprint of photoevaporation on edge-on discs* MNRAS 411, 1104

Owen, J. E.; Ercolano, B.; Clarke, C. J.; Alexander, R. D. 2010 *Radiation-hydrodynamic models of X-ray and EUV photoevaporating protoplanetary discs* MNRAS 401, 1415

Birnstiel, T.; Klahr, H.; Ercolano, B. 2012 *A simple model for the evolution of the dust population in protoplanetary disks* A&A 539, 148

Dominik, C., Dullemond, C.P. 2011 *Accretion through the inner hole of transitional disks: what happens to the dust?* A&A, 531, 101

Ramsey, J.P., Dullemond, C. P. 2015 *Radiation hydrodynamics including irradiation and adaptive mesh refinement with AZEuS. I. Methods* A&A, 574, 81

Gorti, U., Hollenbach, D., Dullemond, C.P. 2015 *The Impact of Dust Evolution and Photoevaporation on Disk Dispersal* ApJ, 804, 29

Juhász, A., Benisty, M., Pohl, A., Dullemond, C.P., Dominik, C., Paardekooper, S.-J. 2015 *Spiral arms in scattered light images of protoplanetary discs: are they the signposts of planets?* MNRAS, 451, 147

Pohl, A., Pinilla, P., Benisty, M., Ataiee, S., Juhász, A., Dullemond, C.P., Van Boekel, R., Henning, T. 2015 *Scattered light images of spiral arms in marginally gravitationally unstable discs with an embedded planet* MNRAS, 453, 1768

**Project D1** PI: W. Kley Co-PI: C. P. Dullemond

Kley W., Bitsch, B. & Klahr, H.H. (2009) *Planet migration in three-dimensional radiative discs.* A&A 506, 971

Paardekooper, S.-J., Baruteau, C., Crida, A. & Kley W. (2010) *A torque formula for non-isothermal type I planetary migration - I. Unsaturated horseshoe drag* MNRAS 401, 1950

Kley W., Nelson, R.P. (2012) *Planet-Disk Interaction and Orbital Evolution* ARAA 50, 211

Müller, T. & Kley, W. (2013) *Modelling accretion in transitional disks* A&A 560, A40.

Müller, T. Kley, W. & Meru, F. (2012) *Treating gravity in thin-disk simulations* A&A 541, A123.

Andrews, S.M., Wilner, D., Espaillat, C., Hughes, A.M., Dullemond, C.P., McClure, M.K., Qi, C., Brown, J.M. 2011 *Resolved Images of Large Cavities in Protoplanetary Transition Disks*, ApJ, 732, 42

Dominik, C., Dullemond, C.P. 2011 *Accretion through the inner hole of transitional disks: what happens to the dust?* A&A, 531, 101

Ataiee, S., Pinilla, P., Zsom, A., Dullemond, C.P., Dominik, C., Ghanbari, J. 2013 *Asymmetric transition discs: Vorticity or eccentricity?* A&A, 553, L3

Brinch, C. & Dullemond, C.P. 2014 *Interferometer predictions with triangulated images: solving the multiscale problem*, MNRAS, 440, 3285-3291

Pohl, A., Pinilla, P., Benisty, M., Ataiee, S., Juhász, A., Dullemond, C.P., Van Boekel, R., Henning, T. 2015 *Scattered light images of spiral arms in marginally gravitationally unstable discs with an embedded planet* MNRAS, 453, 1768

**Project D2** PI: C. P Dullemond Co-PI: W. Kley

Birnstiel, T., Dullemond, C.P., Pinilla, P. 2013 *Lopsided dust rings in transition disks* A&A, 550, 8

Ataiee, S., Pinilla, P., Zsom, A., Dullemond, C.P., Dominik, C., Ghanbari, J. 2013 *Asymmetric transition discs: Vorticity or eccentricity?* A&A, 553, L3 van der Marel, N., van Dishoeck, E.F., Bruderer, S., Birnstiel, T., Pinilla, P., Dullemond, C.P., van Kempen, T.A., Schmalzl, M., Brown, J.M., Herczeg, G.J., Mathews, G.S., Geers, V. 2013 *A Major Asymmetric Dust Trap in a Transition Disk* Science, 340, 1199

Kataoka, A., Muto, T., Momose, M., Tsukagoshi, T., Fukagawa, M., Shibai, H., Hanawa, T., Murakawa, K., Dullemond, C.P. 2015 *Millimeter-wave Polarization of Protoplanetary Disks due to Dust Scattering* ApJ, 809, 78

Pohl, A., Pinilla, P., Benisty, M., Ataiee, S., Juhász, A., Dullemond, C.P., Van Boekel, R., Henning, T. 2015 *Scattered light images of spiral arms in marginally gravitationally unstable discs with an embedded planet*, 2015, MNRAS, 453, 1768

Kley W., Nelson, R.P. (2012) *Planet-Disk Interaction and Orbital Evolution* ARAA 50, 211

Müller, T. & Kley, W. (2013) *Modelling accretion in transitional disks* A&A 560, A40.

Müller, T. Kley, W. & Meru, F. (2012) *Treating gravity in thin-disk simulations* A&A 541, A123

Kuiper, R., Klahr, H., Dullemond, C., Kley, W. & Henning, T. (2010) *Fast and accurate frequency-dependent radiation transport for hydrodynamics simulations in massive star formation* A&A 511, A81

Kley, W. & Haghighipour, N. (2014) *Modeling circumbinary planets: The case of Kepler-38* A&A 564, A72.

## Barbara Ercolano: Curriculum Vitae

| | | |
|---|---|---|
| DATE OF BIRTH | August 7, 1977 | |
| PLACE OF BIRTH | San Giorgio a Cremano (Napoli), Italy | |
| EDUCATION | 1999 | Msci Astrophysics, University College London, UK |
| | 2002 | PhD in astronomy, University College London |
| EMPLOYMENT | Dec 2010-today | Professor of Theoretical Astrophysics<br>Ludwig-Maximilians Universität München |
| | Mar 2010 - Nov 2010 | Lecturer of Astrophysics<br>University of Exeter, UK |
| | Jan 2008 - Feb 2010 | Advanced Fellow/ Institute of Astronomy<br>University of Cambridge/ UCL UK |
| | Aug 2006 -Jan 2008 | Research assistant / Center for Astrophysics<br>Harvard / Smithsonian, Cambridge MA (USA) |
| | Jan 2003 - Jul 2006 | Research assistant / Dept of Astronomy<br>University College London, UK |
| AWARDS | STFC Advanced fellowship (2009)<br>Royal Astronomical Society Fowler Price for Early Career Achievements (2010) | |
| RESEARCH INTERESTS | Star and planet formation, interstellar medium evolution and enrichment, computational methods, radiative transfer | |

Ten most important publications:

Ercolano, B.; Barlow, M. J.; Storey, P. J.; Liu, X.-W. 2003, *MOCASSIN: a fully three-dimensional Monte Carlo photoionization code*, MNRAS 340, 1136

Ercolano, B.; Barlow, M. J.; Storey, P. J. 2005, *The dusty MOCASSIN: fully self-consistent 3D photoionization and dust radiative transfer models*, MNRAS 362, 1038

Sugerman, B.; Ercolano, B. et al. 2006, *Massive-Star Supernovae as Major Dust Factories*, Science 313, 196S

Ercolano, B.; Drake, J. J.; Raymond, J. C.; Clarke, C. J. 2008 *X-Ray-Irradiated Protoplanetary Disk Atmospheres. I. Predicted Emission-Line Spectrum and Photoevaporation* ApJ 688, 398

Ercolano, Barbara; Young, Peter R.; Drake, Jeremy J.; Raymond, John C. 2008 *X-Ray Enabled MOCASSIN: A Three-dimensional Code for Photoionized Media* ApJS 175, 534

Ercolano, B.; Clarke, C. J.; Drake, J. J. 2009 *X-Ray Irradiated Protoplanetary Disk Atmospheres. II. Predictions from Models in Hydrostatic Equilibrium* ApJ 699, 1639

Owen, J. E.; Ercolano, B.; Clarke, C. J.; Alexander, R. D. 2010 *Radiation-hydrodynamic models of X-ray and EUV photoevaporating protoplanetary discs*MNRAS 401, 1415O

Ercolano, B.; Owen, J. E. 2010 *Theoretical spectra of photoevaporating protoplanetary discs: an atlas of atomic and low-ionization emission lines* MNRAS 406, 1553

Dale, J. E.; Ercolano, B.; Bonnell, I. A. 2012 *Ionizing feedback from massive stars in massive clusters - II. Disruption of bound clusters by photoionization* MNRAS 424, 377

Casassus, S. et al. 2013 *Flows of gas through a protoplanetary gap* Nature 493, 191

## Cornelis Petrus Dullemond: Curriculum Vitae

| | | |
|---|---|---|
| DATE OF BIRTH | December 11, 1970 | |
| PLACE OF BIRTH | Nijmegen, the Netherlands | |
| EDUCATION | 1994 | Msci physics, University of Amsterdam, the Netherlands |
| | 1999 | PhD in astrophysics, Leiden University, the Netherlands |
| EMPLOYMENT | Jul 2015 - today | Director of the Center for Astronomy Heidelberg (ZAH) |
| | Oct 2012 - today | Director of the Institute for Theoretical Astrophysics (ITA) |
| | Nov 2010 - today | Professor at Heidelberg University |
| | Jul 2006 - Aug 2011 | Max Planck Research Group leader at the MPIA Heidelberg |
| | Oct 2004 - Jun 2006 | Senior postdoc at the MPIA Heidelberg |
| | Feb 2002 - Oct 2004 | Postdoctoral Fellow at MPA Garching |
| | Oct 1999 - Feb 2002 | Postdoc in a RTN at MPA Garching |
| RESEARCH INTERESTS | Numerical diagnostic radiative transfer, dust growth, protoplanetary disk models, numerical hydrodynamics and radiation hydrodynamics, algorithm design. | |

Ten most important publications:

Dullemond, C.P. & Dominik, C., *Dust coagulation in protoplanetary disk: a too rapid depletion of small grains*, 2005, A&A 434, 971

Birnstiel, T., Ricci, L., Trotta, F., Dullemond, C.P., Natta, A., Testi, L., Dominik, C., Henning, Th., Ormel, C.W., Zsom, A., *Testing the theory of grain growth and fragmentation by millimeter observations of protoplanetary disks*, 2010, ApJL, 516, L14

Regály, Zs., Juhász, A., Sándor, Zs., Dullemond, C.P., *Possible planet-forming regions on submillimetre images*, 2012, MNRAS, 419, 1701

Pinilla, P., Birnstiel, T., Ricci, L., Dullemond, C.P., Uribe, A.L., Testi, L., Natta, A., *Trapping dust particles in the outer regions of protoplanetary disks*, 2012, A&A 538, 114

Ataiee, S., Pinilla, P., Zsom, A., Dullemond, C.P., Dominik, C., Ghanbari, J., 2013 *Asymmetric transition discs: Vorticity or eccentricity?*, 2013, A&A, 553, L3

van der Marel, N., van Dishoeck, E.F., Bruderer, S., Birnstiel, T., Pinilla, P., Dullemond, C.P., van Kempen, T.A., Schmalzl, M., Brown, J.M., Herczeg, G.J., Mathews, G.S., Geers, V. *A Major Asymmetric Dust Trap in a Transition Disk*, 2013, Science, 340, 1199

Drazkowska, J., Dullemond, C.P. *Can dust coagulation trigger streaming instability?*, 2014, A&A, 572, 78

Ramsey, J.P., Dullemond, C. P. *Radiation hydrodynamics including irradiation and adaptive mesh refinement with AZEuS. I. Methods*, 2015, A&A, 574, 81

Kataoka, A., Muto, T., Momose, M., Tsukagoshi, T., Fukagawa, M., Shibai, H., Hanawa, T., Murakawa, K., Dullemond, C.P. *Millimeter-wave Polarization of Protoplanetary Disks due to Dust Scattering*, 2015, ApJ, 809, 78

Pohl, A., Pinilla, P., Benisty, M., Ataiee, S., Juhász, A., Dullemond, C.P., Van Boekel, R., Henning, T. *Scattered light images of spiral arms in marginally gravitationally unstable discs with an embedded planet*, 2015, MNRAS, 453, 1768

## Leonardo Testi: Curriculum Vitae

| | | |
|---|---|---|
| EDUCATION | 1993 | Masters Astronomy Universita' degli Studi di Firenze, Italy |
| | 1997 | PhD in astronomy,Universita' degli Studi di Firenze, Italy |
| | 2003 | Italian ÓAbilitazione Scientifica NazionaleÓ for Full Professors |
| EMPLOYMENT | 2007-today | Full Astronomer and European ALMA Programme Scientist„ ESO, Garching, Germany |
| | 2003-today | Astronomo Associato California Institute of Technology, USA |
| | 1998-2003 | Ricercatore Astronomo Osservatorio Astrofisico di Arcetri, Italy |
| | 1997-1999 | Postdoctoral Scholar University of Florida, Gainesville, FL, USA |
| RESEARCH INTERESTS | observational studies of the properties and evolution of protoplanetary disks towards the formation of planetary systems and the formation and early evolution of sub-stellar objects, stars and clusters in our Galaxy and the Local Universe. | |

Ten most important publications:

Testi, L.; Sargent, A. I. 1998 *Star Formation in Clusters: A Survey of Compact Millimeter-Wave Sources in the Serpens Core* ApJ 508L 91

Natta, A.; Testi, L.; Neri, R.; Shepherd, D. S.; Wilner, D. J. 2004 *A search for evolved dust in Herbig Ae stars* A&A 416, 179

Testi, L.; Natta, A.; Shepherd, D. S.; Wilner, D. J. 2003 *Large grains in the disk of CQ Tau* A&A 403, 323

Natta, A.; Testi, L.; Muzerolle, J.; Randich, S.; ComerŮn, F.; Persi, P. 2004 *Accretion in brown dwarfs: An infrared view* A&A 424, 603

Whelan, E. T.; Ray, T. P.; Bacciotti, F.; Natta, A.; Testi, L.; Randich, S. 2005 *A resolved outflow of matter from a brown dwarf* Nature 435, 652

Natta, A.; Testi, L.; Randich, S. 2006 *Accretion in the $\rho$-Ophiuchi pre-main sequence stars* A&A 452, 245

Isella, A.; Testi, L.; Natta, A. 2006 *Large dust grains in the inner region of circumstellar disks* A&A 451, 951

Isella, A.; Testi, L.; Natta, A.; Neri, R.; Wilner, D.; Qi, C. 2007 *Millimeter imaging of HD 163296: probing the disk structure and kinematics* A&A 469, 213

Ricci, L.; Testi, L.; Natta, A.; Neri, R.; Cabrit, S.; Herczeg, G. J. 2010 *Dust properties of protoplanetary disks in the Taurus-Auriga star forming region from millimeter wavelengths* 2010 A&A 512, 15

Testi, L. et al. 2014 *Dust Evolution in Protoplanetary Disks* Protostars and Planets VI, 339

## Paola Caselli: Curriculum Vitae

| | | |
|---|---|---|
| EDUCATION | 1990 | Masters Astronomy Universita' di Bologna, Italy |
| | 1994 | PhD in astronomy,Universita' di Bologna, Italy |
| EMPLOYMENT | 2014-today | Director, Max-Planck-Institute for Extraterrestrial Physics, Garching, Germany |
| | 2014-today | Honorary Professor<br>Ludwig-Maximilians-Universitaet, Muenchen, Germany |
| | 2014-today | Visiting Professor<br>University of Leeds, UK |
| | 2012 - today | Courtesy Professor<br>University of Florida, Gainesville, FL, USA |
| | 2007-2014 | Professor of Astronomy<br>University of Leeds, UK |
| | 2009-2011 | Head of Astrophysics<br>University of Leeds, UK |
| | 1995-2007 | Researcher<br>INAFÐOsservatorio Astrofisico di Arcetri, Firenze, Italy |
| | 2006-2007 | Visiting Scholar<br>Harvard University, Cambridge, MA, USA |
| | 2005 | Visiting Scientist<br>UC Berkeley, USA |
| | 2001-2007 | Visiting Senior Research Fellow<br>University of Leeds, UK |
| | 1995 | Postdoctoral Fellow<br>Max-Planck-Institut f§r Exterrestrische Physik, Garching, Germany |
| | 1994-1995 | Postdoctoral Fellow<br>Smithsonian Astrophysical Observatory, Cambridge, MA, USA. |
| | 1993-1994 | Smithsonian Predoctoral Fellow<br>HarvardÐSmithsonian Center for Astrophysics, Cambridge, MA, USA. |
| | 1992-1993 | Visiting Student<br>HarvardÐSmithsonian Center for Astrophysics, Cambridge, MA, USA. |
| | 1992 | Visiting Student<br>The Ohio State University, Columbus, OH, USA |
| | 1991-1992 | Fellowship<br>the Istituto di Spettroscopia Molecolare, C.N.R., Bologna, Italy |
| AWARDS | ERC Advanced Grant | |
| RESEARCH INTERESTS | Astrochemistry of prestellar cores, high mass star formation, shcks, young protoplanetary discs, high redshift galaxies, surface chemistry, molecular spectroscopy | |

Ten most important publications:


Evans, M. G. et al. 2015 *Gravitatiogarnal instabilities in a protosolar-like disc I: dynamics and chemistry* MRAS 453, 1147

Caselli, P. et al. 2012 *First Detection of Water Vapor in a Pre-stellar Core* ApJ 759, 37

Caselli, P.; Ceccarelli, C. 2012 *Our astrochemical heritage* A&ARv 20, 56

Ilee, J. D., Boley, A. C., Caselli, P., et al. 2011 *Chemistry in a gravitationally unstable protoplanetary disc* MNRAS, 417, 2950

Keto, E.; Caselli, P. 2010 *Dynamics and depletion in thermally supercritical starless cores* MNRAS 402, 1625

Caselli, P.; Vastel, C.; Ceccarelli, C.; van der Tak, F. F. S.; Crapsi, A.; Bacmann, A. 2008 *Survey of ortho-H2D+ (11,0-11,1) in dense cloud cores* A&A 492, 703

Crapsi, A.; Caselli, P.; Walmsley, M. C.; Tafalla, M. 2007 *Observing the gas temperature drop in the high-density nucleus of L 1544* A&A 470, 221

Crapsi, A.; Caselli, P.; Walmsley, C. M.; Myers, P. C.; Tafalla, M.; Lee, C. W.; Bourke, T. L. 2005 *Probing the Evolutionary Status of Starless Cores through N2H+ and N2D+ Observations* ApJ 619, 379

Caselli, P.; Benson, P. J.; Myers, P. C.; Tafalla, M. 2002 *Dense Cores in Dark Clouds. XIV. N2H+ (1-0) Maps of Dense Cloud Cores* ApJ 572. 238

Caselli, P.; Walmsley, C. M.; Tafalla, M.; Dore, L.; Myers, P. C. 1999 *CO Depletion in the Starless Cloud Core L1544* ApJ 523, 165

## Thomas Preibisch: Curriculum Vitae

| | | |
|---|---|---|
| DATE OF BIRTH | March 7, 1965 | |
| PLACE OF BIRTH | Cham, Germany | |
| EDUCATION | 1986-1988 | Studies in Physics at the University of Regensburg, Germany |
| | 1988-1992 | Studies in Physics at the University of Würzburg, Germany |
| | 1992 | Diploma in Physics, University of Würzburg, Germany |
| | 1995 | PhD Physics, University of Würzburg, Germany |
| EMPLOYMENT | 2008-today | Professor for Astronomy at the University Observatory Ludwig-Maximilians-Universität München |
| | 1999-2008 | Staff Scientist Max Planck Institute for Radio Astronomy, Bonn |
| | in 1997 & 2001 | Guest Scientist Institute for Astronomy, University of Hawaii, Honolulu, USA |
| | 1995-1998 | Postdoc at the Astronomical Institute, University of Würzburg, Germany |
| RESEARCH INTERESTS | observational studies of stellar X-ray, protoplanetary disk studies and star formation. | |

Ten most important publications:

Th. Preibisch, 2004, *X-ray Activity and Accretion in Young Stellar Objects*, AspS 292, 631Ð641

Th. Preibisch, et al. 2005 *The Origin of T Tauri X-ray Emission: New Insights from the Chandra Orion Ultradeep Project* ApJS 160, 401Ð422

Th. Preibisch, E.D. Feigelson, 2005 *The Evolution of X-Ray Emission in Young Stars* ApJS 160, 390Ð400

J. Forbrich, Th. Preibisch, K.M. Menten, 2006, *Radio and X-ray variability of young stellar objects in the Coronet cluster*, A&A, 446, 155Ð170

Th. Preibisch, S. Kraus, Th. Driebe, R. van Boekel, G. Weigelt, 2006 *A compact dusty disk around the Herbig Ae star HR 5999 resolved with VLTI / MIDI*, A&A 458, 235Ð243

S. Kraus, Th. Preibisch, K. Ohnaka, 2008 *Detection of an Inner Gaseous Component in a Herbig Be Star Accretion Disk: Near- and Mid-Infrared Spectrointerferometry and Radiative Transfer modeling of MWC 147* ApJ 676, 490Ð508

Th. Preibisch et al. 2011 *Near-Infrared properties of the X-ray emitting young stellar objects in the Carina Nebula* ApJS, 194, 10

Th. Preibisch, Th. Ratzka, T. Gehring, H. Ohlendorf, H. Zinnecker, R.R. King, M.J. Mc- Caughrean, 2011 *Detection of a large massive circumstellar disk around a high-mass young stellar object in the Carina Nebula* A&A 530, A40

B. Gaczkowski, Th. Preibisch, Th. Ratzka, V. Roccatagliata, H. Ohlendorf, H. Zinnecker 2012 *Herschel far-infrared observations of the Carina Nebula complex. II. The embedded young stellar and protostellar population* A&A 541, A132

Th. Preibisch, M. Mehlhorn, L. Townsley, P. Broos, Th. Ratzka, 2014 *Chandra X-ray observation of the HII region Gum 31 in the Carina nebula complex* A&A 564, A120

## Wilhelm Kley: Curriculum Vitae

| | | |
|---|---|---|
| DATE OF BIRTH | February 19, 1958 | |
| PLACE OF BIRTH | Soest, Germany | |
| EDUCATION | 1985 | Physics Diploma, University of Munich, Germany |
| | 1988 | Dissertation in Physics, University of Munich, Germay |
| | 1997 | Habilitation, University of Jena |
| EMPLOYMENT | 2000-today | Full Professor (Director of the Institute of Astronomy & Astrophysics in turn), University of Tübingen, Germany |
| | 1999-2000 | Max-Planck Institute for Astronomy, Heidelberg, Germany |
| | 1993-1996 | Max-Planck Research Group *Gravitational Theory*, Jena |
| | 1992-1993 | Queen Mary College, University of London, UK |
| | 1990-1993 | UC Santa Cruz, USA |
| | 1986-1990 | University of Munich, Germany |
| AWARDS | Speaker DFG Research Unit *Planet Formation: Critical first growth phase*, 2007-2013 | |
| RESEARCH INTERESTS | Planet formation, planet disc interactions, hydrodynamics | |

Ten most important publications:

Kley, W. (1999) *Mass Flow and Accretion through gaps in Accretion discs.* M.N.R.A.S., **303**, 969

D'Angelo, G., Kley, W. & Henning, Th. (2003) *Orbital Migration and Mass Accretion of Protoplanets in Three-dimensional Global Computations with Nested Grids.* Astrophys. J., **586**, 540

Kley W. & Crida, A. (2008) Migration of protoplanets in radiative discs. *Astron. Astrophys*, **487**, L9

Kley W., Bitsch, B. & Klahr, H.H. (2009) *Planet migration in three-dimensional radiative discs.* Astron. Astrophys, **506**, 971

Paardekooper, S.-J., Baruteau, C., Crida, A. & Kley W. (2010) *A torque formula for non-isothermal type I planetary migration - I. Unsaturated horseshoe drag.* M.N.R.A.S., **401**, 1950

Kuiper, R., Klahr, H., Dullemond, C., Kley, W. & Henning, T. (2010) *Fast and accurate frequency-dependent radiation transport for hydrodynamics simulations in massive star formation*, Astronomy & Astrophysics, **511**, A81.

Kley W., Nelson, R.P. (2012) *Planet-Disk Interaction and Orbital Evolution*, Annual Review of Astronomy and Astrophysics, **50**, 211

Müller, T. & Kley, W. (2013) *Modelling accretion in transitional disks*, Astronomy & Astrophysics, **560**, A40.

Kolb, S. M., Stute, M., Kley, W. & Mignone, A. (2013) *Radiation hydrodynamics integrated in the PLUTO code*, Astronomy & Astrophysics, **559**, A80.

Kley, W. & Haghighipour, N. (2014) *Modeling circumbinary planets: The case of Kepler-38*, Astronomy & Astrophysics, **564**, A72.

# FORSCHERGRUPPE-PROPOSAL:

# "Planet Formation Witnesses and Probes: Transition Discs"

# FINANCIAL OVERVIEW (EURO PER YEAR)

**Salaries**

| | | |
|---|---|---|
| 4 positions for PhD Students at 50% | (4. x 0.5 x 60,600) | 121200 € |
| 4 positions for Postdocs | (4 x 65,400) | 261600 € |
| ***Subtotal salaries per year*** | | ***382800 €*** |

Technical equipment for the three years

Multicore machine for the simulations (see attached Quote) **29251/3** **9750** €

Consumption Material

No investment necessary

**Publication Expenses**

8 positions x 700 euro **5600** €

**Travel Expenses**

*Forschergruppe meetings*

Kick off and Wrap up meetings
2 Three Day meetings with approximately 30 participants -
including collaborators from overseas 30000 € for the first 3 years 10000 €

2 Yearly two day meetings of the whole collaboration 20000 €

Collaboration meetings between individual projects
2 x two day meetings with 2 PhD students and 2 participating scientists 8000 €

Exchange of PhD students and postdocs
8 x three week stay 20000 €

*Conferences*

National Conferences 10000 €

International Conferences 25000 €

***Subtotal travel per year*** ***93000 €***

**TOTAL ASKED FUNDING PER YEAR** **491150** €

**microstaxx® Ihr IT-Systemhaus**
Microstaxx Gesellschaft für Informations- & Kommunikationslösungen mbH · info@microstaxx.de
Wilhelm-Kuhnert-Straße 26 · 81543 München · Fon +49-89-489075-0 · Fax +49-89-489075-99
Amtsgericht München · HRB-Nummer 98809 · Geschäftsführer: Christian Hoffmann, Martin Reil

microstaxx

microstaxx GmbH Wilhelm-Kuhnert-Straße 26 81543 München

**LMU - Ludwig-Maximilians-Universität München**
**Universitäts-Sternwarte**
**Dr. Rudolf Gabler**
**Scheinerstraße 1**
**D - 81679 München**

München, den 23.07.2015

# *Angebot 81001*

| *Angebot Nummer* | *Angebot vom* | *Ihre Kundennummer* | *Ihr Ansprechpartner für dieses Angebot* | *Lieferung erfolgt als (Änderung bitte angeben)* |
|---|---|---|---|---|
| **81001** | **23.07.2015** | **31828** | **Christian Böhm / christian.boehm@microstaxx.de** | **Komplettlieferung** |

*Betrifft / Ihre Referenz:*

1 * Fujitsu Primergy RX4770 M1

Ihre Anfrage vom 22.07.2015

| Pos | Artikel | Bezeichnung | Menge | Preis | Gesamt |
|---|---|---|---|---|---|
| 10 | FSC25947 | Fujitsu-Technology PRIMERGY RX4770 M1 12 core | 1 | 24.580,92 € | **24.580,92 €** |

Fujitsu-Technology PRIMERGY RX4770 M1 12 core

Grundausstattung:
"Rack-Einschub 19"" (4HE) incl. 8x hot plug Lüfter (7+1 redundanz); Systemboard für 4x XEON E7-x800v2 Prozessoren; 2x Memoryboard für je 12x DDR3 LV DIMM Module; 8 Einbauplätze für hot plug 2.5"" SAS/SATA HDD/SSD; iRMC S4 Server Management mit Grafik Controller und 10/100/1000Mbit Service LAN-Port; 1x Dual-Port Ethernet Controller (= 2x 10/1 GBit 10BaseT LANPorts) WOL fähig; SAS RAID Controller optional; LocalView LCD Display; ServerView Suite Software Paket

Original Fujitsu Garantieerweiterung auf fünf Jahre vor Ort-Service nächster Arbeitstag Antrittszeit, 9x5
zu geschäftsüblichen Zeiten Montag bis Freitag 08:00 bis 17:00 Uhr
Herst# FSP:GM5S20000DEPX6

Lieferausstattung:
1 x PRIMERGY RX4770 M1 / Herst# S26361-K1484-V200
4 x Intel Xeon E7-4850v2 12C/24T 2.3GHz 24MB / Herst# S26361-F5308-E450
2 x Memory Board RX4770 M1 / Herst# S26361-F5295-E100
2 x Memory Board RX4770 M1) / Herst# S26361-F5295-E100 3)
8 x 16GB (2x8GB) 1Rx4 L DDR3-1600 R ECC) / Herst# S26361-F5309-E642
16 x 32GB (2x16GB) 2Rx4 L DDR3-1600 R ECC) / Herst# S26361-F5309-E643
1 x Memory Lockstep Mode Installation / Herst# S26361-F5295-E1
6 x HD SAS 6G 300GB 10K HOT PL 2.5" EP / Herst# S26361-F3818-E130
2 x SSD SATA 6G 100GB Main 2.5" H-P EP / Herst# S26361-F3821-E100
1 x PRAID EP420i / Herst# S26361-F5243-E2
1 x SAS cable set for PRAID EP4x0i / Herst# S26361-F5295-E620
1 x TFM Modul für FBU auf PRAID EP420i/e / Herst# S26361-F5243-E200
1 x RAID Ctrl FBU Option mit 70cm Kabel / Herst# S26361-F5243-E170
1 x PFC EP LPe16002 / Herst# S26361-F4994-E2
1 x Rack Mount Kit F2-C LV / Herst# S26361-F2735-E285
1 x Einbau in symmetrische Racks / Herst# S26361-F4530-E10
1 x Region-Kit APAC/EMEA/Indien / Herst# S26361-F1452-E100
1 x iRMC S4 advanced pack / Herst# S26361-F1790-E243
4 x Stromversorgungsmodul 1200W (ohne Kabel) / Herst# S26113-F5295-E120
4 x Leitung Netzanschluss Rack, 4m, schwarz / Herst# T26139-Y1968-E100
1 x Konfigurationshilfe für nicht aktive Komponenten) / Herst# V:NO_T50_RELEASE 3)
1 x TP 5J VO Svc,NBD Az,9x5 / Herst# FSP:GM5S20000DEPX6

Hinweis: Bei diesem Gerät handelt es sich um eine Built-To-Order Konfiguration. Storno oder Rückgabe sind hier herstellerbedingt NICHT möglich !

*Lieferzeit: ca. 2 bis 3 Wochen*

| Pos | Artikel | Bezeichnung | Menge | Preis | Gesamt |
|---|---|---|---|---|---|

| Gesamtbetrag netto | Fracht & Verpackung | 19 % Mwst | **Gesamtbetrag** |
|---|---|---|---|
| **24.580,92 €** | **0,00 €** | **4.670,37 €** | **29.251,29 €** |

Zahlungsbedingungen: **Innerhalb von 14 Tagen ohne Abzug**

Lieferbedingungen: **Frei Haus per UPS**

Es gelten unsere allgemeinen Geschäftsbedingungen (http://www.microstaxx.de/agb/)

Das microstaxx Quick-Order Feld
Einfach ausfüllen und an
089 / 48 90 75 - 99 faxen !
**Bitte alle Seiten faxen !!**

**Hiermit bestellen wir das Angebot 81001 wie oben aufgeführt:**
(nicht benötigte Komponenten können gestrichen werden / Stückzahlen nach Wunsch einfach ändern !)

| Kundenstempel: | Datum | Name des Bestellers in Klarschrift |
|---|---|---|
| | Ihre Bestellangaben | rechtsverbindliche Unterschrift |

*Aufgrund der volatilen Wechselkurssituation US$/EUR gelten viele Preise derzeit als Tagespreise. Bitte erfragen Sie tagesaktuelle Angebote in unserem Vertrieb. Für Ausschreibungen und Rahmenverträge gelten die gesondert vereinbarten Bedingungen.*

Mon. Not. R. Astron. Soc. **000**, 1–7 (2011) Printed 9 May 2016 (MN LaTeX style file v2.2)

# Blueshifted [OI] lines from protoplanetary discs: the smoking gun of X-ray photoevaporation.

Barbara Ercolano[1,2⋆], James E. Owen[3,4]
[1] *Universitäts-Sternwarte München, Scheinerstr. 1, 81679 München, Germany*
[2] *Excellence Cluster Origin and Structure of the Universe, Boltzmannstr.2, 85748 Garching bei München, Germany*
[3] *Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*
[4] *Hubble Fellow*

9 May 2016

**ABSTRACT**

Photoevaporation of protoplanetary discs by high energy radiation from the central young stellar object is currently the favourite model to explain the sudden dispersal of discs from the inside out. While several theoretical works have provided a detailed pictured of this process, the direct observational validation is still lacking. Emission lines produced in these slow moving protoplanetary disc winds may bear the imprint of the wind structure and thus provide a potential diagnostic of the underlying dispersal process. In this paper we primarily focus on the collisionally excited neutral oxygen line at 6300A. We compare our models predictions to observational data and demonstrate a thermal origin for the observed blueshifted low-velocity component of this line from protoplanetary discs. Furthermore our models show that while this line is a clear tell-tale-sign of a warm, quasi-neutral disc wind, typical of X-ray photoevaporation, its strong temperature dependence makes it unsuitable to measure detailed wind quantities like mass-loss-rate.

**Key words:** protoplanetary discs

## 1 INTRODUCTION

Understanding disc dispersal is a key piece in the puzzle of planet formation as it sets the timescale over which (gas giant) planet formation must occur. Furthermore the similarity between the observed timescales over which Young Stellar Objects (YSOs) lose their disc and the theoretically estimated timescale for the formation of planets suggests that the two processes are probably coupled and feed back on each other. The final build up of gaseous planets occurs in discs on their last gasp before dispersal, and the dispersal process itself can lead to rapid evolution of young planets (Owen & Wu, 2016), making evolved discs all the more interesting to study.

A popular model to drive disc dispersal is photoevaporation by radiation from the central star (e.g. Clarke et al. 2001). The exact nature of the driving radiation is however still open to debate. (Extreme and Far) Ultraviolet (UV) radiation as well as X-ray radiation has been shown to be able to drive winds from the disc upper layers (Alexander et al. 2006; Gorti, Hollenbach & Dullemond 2009; Ercolano et al. 2008, 2009; Owen et al. 2010) that are efficient enough to disperse the discs in the observed timescales. However both the location and intensity of the wind depend strongly on the driving radiation, with differences of more than two orders of magnitude for mass loss rates predicted by different models. Thus these different models obviously have profound implications for disc evolution and hence for the formation of planets and their subsequent evolution (e.g. Ercolano & Rosotti 2015).

The presence of a warm, at least partially, ionised disc wind has been confirmed via the observation of a few km/s blue-shift in the profile of the [NeII] 12.8$\mu$m fine structure line (Pascucci et al. 2007). Unfortunately modelling of this line cannot shed light on the radiation source which drives the wind, due to the different routes to formation of the $Ne^{+}$ ion which have different efficiencies in a fully ionised EUV-driven wind and in a quasi-neutral X-ray driven wind. $Ne^{+}$ formation occurs via the removal of a valence electron from Ne atoms in the fully-ionised winds driven by EUV radiation. In an X-ray driven wind $Ne^{+}$ is predominantly produced via charge exchange of $Ne^{2+}$ with neutral H atoms, which are abundant in the quasi-neutral winds driven by X-rays. Atomic physics thus conspires to the result that both an EUV- and an X-ray driven wind, whose mass-loss rates differ by over two orders of magnitude, can equally well fit

⋆ E-mail: ercolano@usm.lmu.de (BE)

the observations (Ercolano & Owen 2010; Alexander 2008; Pascucci et al. 2011).

Forbidden lines from low-ionisation and atomic states of common elements may present an alternative way to study the wind dispersal mechanism. In particular a few km/s blueshift has been measured in the profiles of, for example, the [OI] 6300, [O I] 5577, [S II] 6731, and [N II] 6583 lines (e.g. Hartigan et al. 1995, White & Hillenbrand 2004, Mohanty et al. 2005, Rigliaco et al. 2013, Natta et al. 2014). The profiles are often double-peaked, with one component blue-shifted to a few hundred km/s (high velocity component, HVC) and a second component typically blue-shifted by only a few km/s (low velocity component, LVC), typical of a photoionised wind. The HVC is generally attributed to emission from a dense outflows closer to the star or jets (Hartigan et al. 1995). The collisionally excited neutral oxygen line at 6300A, in particular, gained significant attention for its potential to discriminate between an EUV- and an X-ray driven wind. EUV-driven winds are, by construction, fully ionised and cannot match the observed luminosities of the LVCs of the [OI] 6300 line (Font et al. 2004). X-ray winds, on the other hand, are only weakly ionised and warm enough to produce the [OI] 6300 line.

Ercolano & Owen (2010, EO10) calculated synthetic spectra from the X-ray photoevaporation models of Owen et al. (2010,2011), providing an atlas of atomic and low-ionising emission lines, including the [OI] 6300 line. The line intensities and profiles predicted by EO10 were in agreement with the observations available at the time, thus suggesting that the blue-shifted LVC of the [OI] 6300 line is produced via collisional excitation of neutral oxygen atoms with electrons and hydrogen atoms in the slow-moving photoevaporative winds driven by X-ray radiation.

Later observational studies by Rigliaco et al. (2013) and Natta et al. (2014) showed some significant inconsistencies between the model predictions of the [OI] 6300 line by EO10 and the new data. **This led Rigliaco et al. (2013) to suggest a non-thermal origin for the [OI] 6300 line (see also Gorti et al. 2011). Natta et al. (2014), on the other hand, still argue against a non-thermal origin of the OI lines, based on the simultaneous presence of the [SII] 4068 line in their spectra.**

In this paper we revisit the theoretical models in light of these later observations and show that the [OI] 6300 data can be indeed explained in the context of an X-ray driven photoevaporative wind and confirm a thermal origin for this line. We show that the over-simplistic scaling of the illuminating flux in the work by EO10 is to blame for the misleading conclusions on the origin of the [OI] 6300. In Section 2 we present the methods employed in our study. In Section 3 we describe the modelling strategy and present the results. A final discussion and our conclusions are given in Section 4.

## 2 METHODS

### 2.1 X-ray photoevaporative wind structure

We use the set of wind solutions (density and velocity distribution of gas in the wind) for primordial discs **(i.e. gas-rich, optically thick discs, which do not have an evacuated inner cavity)** calculated by Owen et al. (2010,2011) and EO10 for a 0.7 $M_\odot$ star and X-ray luminosities (0.1 keV $\leqslant h\nu \leqslant$ 10 keV) of $L_X = 2\times10^{28}, 2\times10^{29}$ and $2\times10^{30}$ erg/sec. These were obtained by means of two-dimensional hydrodynamic calculations using the ZEUS code (Stone et al. 1992a,b,c; Hayes et al. 2006), modified to include the effects of X-ray irradiation with a parametrisation of the gas temperature as a function of the local ionisation parameter. The dust radiative transfer and photosionisation code MOCASSIN (Ercolano et al. 2003, 2005, 2008b), modified according to Ercolano et al (2008a), was used produce the temperature parametrisation. The atomic database of the MOCASSIN code included opacity data from Verner et al. (1993) and Verner & Yakovlev (1995), energy levels, collision strengths and transition probabilities from Version 5.2 of the CHIANTI database (Landi et al. 2006, and references therein) and hydrogen and helium free-bound continuous emission data of Ercolano & Storey (2006). The ionising spectrum used to calculate the temperature parametrisation was calculated by Ercolano et al (2009a), using the plasma code of Kashyap & Drake (2000) from an emission measure distribution based on that derived for RS CVn type binaries by Sanz-Forcada et al. (2002), which peaks at $10^4$ K and fits to Chandra spectra of T-Tauri stars by Maggio et al. (2007), which peaks at around $10^{7.5}$ K. This spectrum has a significant EUV component (13.6 eV $\leqslant h\nu \leqslant 0.1keV$), with roughly $L_{EUV} = L_X$. Solar abundances (Asplund et al. 2005), depleted according to Savage & Sembach (1996) were assumed, namely (number density, with respect to hydrogen): $He/H = 0.1, C/H = 1.4\times10^4, N/H = 8.32\times10^5, O/H = 3.2\times10^4, Ne/H = 1.2\times10^4, Mg/H = 1.1\times10^6, Si/H = 1.7\times10^6, S/H = 2.8\times10^5$. More details about the codes and setup of the models can be found in Ercolano et al. (2008a, 2009a) and Owen et al. (2010).

The hydrodynamical calculations where performed in spherical co-ordinates with a domain spanning $[0, \pi/2]$ in the $\theta$ direction and $[r_{\rm in}, r_{\rm out}]$ in the radial direction, with $r_{\rm out}$ set to 100 AU. In the calculations taken from Owen et al. (2010,2011) $r_{\rm in}$ was set to 0.33 AU and a resolution of 100 uniformly spaced cells in the angular direction and 250 non-uniformly spaced cells in the radial was used. As we shall discuss later in order to asses the role of [OI] emission from the bound inner disc ($R < 1$ AU) we perform a new set of hydrodynamical calculations, this time with $r_{\rm in}$=0.04 AU with a resolution of 256 uniformly spaced cells in the angular direction and 384 non-uniformly spaced cells in the radial direction. Since the wind is launched from approximately 1 AU in the calculations, a smaller inner boundary did not effect the dynamics it just gave **the** hydrostatic density and temperature structure of the inner disc which we could use to calculate the [OI] emissivities. In all cases the simulations were run for at least 10 dynamical time-scales at the outer boundary until a steady-state was achieved (see discussion in Owen et al. 2010).

### 2.2 Photoionisation calculations

Following the approach in EO10, we perform photoionisation calculations of the wind structures with the aim of predicting the intensity and spectral profile of the collisionally excited neutral hydrogen line at 6300A and compare it with the observational results of Rigliaco et al. (2013). The MOCASSIN code is employed for this task, with exactly the same settings as described in the previous section. The ionising spectrum we use is the same as described above for the X-ray region, and used by EO10, additionally we consider here a softer spectral component due to accretion on the young stellar object (YSO). The latter is approximated as a blackbody of temperature 12000K and luminosity expressed as a multiple of the stellar bolometric luminosity, $L_{acc} = a \times L_{bol}$, with $a$ ranging from 10 to $10^{-5}$. It is important to note that since the wind itself is driven by the X-rays (in the range 0.1-1 keV), modifying the soft UV spectrum will not effect the dynamics of the wind itself (Owen et al. 2012), and it is thus not necessary to run new wind simulations for the purpose of this work.

### 2.3 Emissivity and line profile calculations

We have used our two-dimensional map of emissivities and gas velocities obtained from MOCASSIN to reconstruct a three-dimensional cube of the disc and calculate the line-of-sight emission profiles for several of the [OI] transitions. The emissivities are calculated using 120 logarithmically spaced radial points ($N_R$=120)[1] and 1500 logarithmically spaced height points ($N_Z$=1500). By assuming azimuthal and reflection symmetry the resultant 3D grid has dimensions $N_R \times 2N_Z \times N_\varphi$, where we adopt a values of $N_\varphi = 400$ which was sufficient to resolve the line profiles. For the [OI] lines the disc atmosphere is optically thin and the contribution to the line can escape freely, provided that the line of sight does not intercept the disc mid-plane which is completely optically thick due to dust (c.f. EC10). We neglect attenuation due to dust in the disc's atmosphere, this will only effect the results for the largest inclinations.

The line luminosity is then computed by including a Doppler broadening term in each cell. Thus, the luminosity at a given velocity $u$ is computed using numerical integration by direct summation, taking the emissivities and velocity to be constant in each cell. Such that the line luminosity at a given velocity $L(u)$ is given by:

$$L(u) = \int \mathrm{d}^3 r \frac{\ell(r)}{\sqrt{2\pi v_{\mathrm{th}}(r)^2}} \exp\left(-\frac{[u - u_{\mathrm{los}}(r)]^2}{2v_{\mathrm{th}}(r)^2}\right) \quad (1)$$

where $\ell(r)$ is the volume averaged power emitted at a point $r$, $u_{\mathrm{los}}$ is the projected gas velocity along the line of sight and $v_{\mathrm{th}}$ is the local rms velocity of the emitting atom. The lines were computed with a velocity resolution of 0.25 km s$^{-1}$. The lines were then degraded to an instrumental resolution of $R = 25,000$ – i.e. the resolution of the Hartigan et al. (1995) and Rigliaco et al. (2013) study – and $R = 50,000$ a higher resolution representative of a future study. The degradation was performed by convolving the line profiles with a Gaussian profile of the appropriate width. The line profiles were calculated for disc inclinations of 0 to 90 degrees at 10 degree intervals.

[1] Note throughout this paper we use $\{r, \theta, \phi\}$ and $\{R, \varphi, z\}$ to distinguish between spherical and cylindrical polar co-ordinates respectfully.

## 3 STRATEGY AND RESULTS

On the basis of their observations Rigliaco et al. (2013) highlighted a number of discrepancies with the models of EO10, which argued against a thermal origin of the [OI] 6300 line in an X-ray driven photoevaporative wind, as suggested by EO10. In particular, in contrast to the models of EO10, the observations showed: (1) no correlation between the [OI] luminosity, $L_{[OI]}$, and the X-ray luminosity, $L_X$, (2) a correlation of $L_{[OI]}$ with the FUV luminosity $L_{FUV}$, (3) higher full width half maximum (FWHM) of the [OI]6300 line and (4) a lower [OI]6300/[OI]5577 ratio.

We will show here that the above discrepancies can be fully explained by considering the assumptions made by EO10, with regards to the ionising spectrum of the central Young Stellar Object (YSO). As described above, the illuminating spectrum used by EO10 extends to the EUV region, with $L_{EUV} = L_X$. In order to explore the relation between of $L_{[OI]}$ and $L_X$, EO10 scaled their *entire* spectrum by the same factor, hence also increasing/decreasing the $L_{EUV}$ reaching the X-ray driven wind. We suggest here that the $L_{[OI]}$-$L_X$ correlation reported by EO10 is actually the $L_{[OI]}$-$L_{EUV}$ correlation, resulting from the homogeneous scaling of the input spectrum at all wavelengths. We demonstrate this here by performing the numerical experiment of decoupling the UV and the X-ray regions of the illuminating spectrum, where we define X-ray/EUV energies higher/lower than 0.1 keV, respectively. Practically we include an additional input spectrum in the form of a blackbody of temperature 12000K, loosely representative of an accretion component, whose luminosity can be scaled independently from the X-ray luminosity. We then set up a grid of models at constant $L_{acc}$ and vary only $L_X$ and a grid of models at constant $L_X$ and vary only $L_{acc}$. The models are summarised in Table 1 and the results are described in the next section.

For the figures presented in this section, we used all the observational data reported in the Rigliaco et al. (2013) study, which was partially based on re-analysis of previous data by Hartigan et al. (1995).

### 3.1 Models at constant accretion luminosity: no correlation with $L_X$

EO10 pubilshed [OI]6300 line intensities obtained from their X-ray photoevaporative wind model of a 0.7 $M_\odot$ star with $L_X = 2 \times 10^{28}, 2 \times 10^{29}$ and $2 \times 10^{30}$ erg/sec. The resulting $L_{[OI]}$ showed a near linear correlation with $L_X$ (filled diamonds in Figure 1), which is not seen in the observations of Rigliaco et al. (2013) (empty symbols in Figure 1). As mentioned already in the previous section, we show here that this apparent correlation is driven by the $L_{EUV}$-$L_X$ correlation in the scaling of the illuminating spectra in the EO10 model. Indeed, as shown by the filled circles in Figure 1, our models with constant accretion luminosity where we vary $L_X$ only do not show any correlation at all between $L_{[OI]}$-$L_X$.

### 3.2 Models at constant X-ray luminosity: correlation with $L_{acc}$

The observations of Rigliaco et al. (2013) showed a clear relation between the $L_{[OI]}$ with the FUV luminosity $L_{FUV}$. We suggest that the observed correlation is explainable in

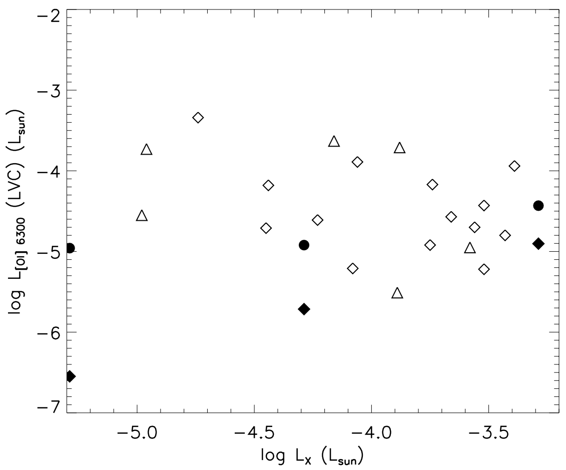


**Figure 1.** [O I] 6300 luminosity versus X-ray luminosity for the subsample of 21 Sample II objects from Rigliaco et al. (2013) (empty diamonds and triangles, where triangles denote upper limits in X-ray luminosity), compared to the model predictions of EO10 (filled diamonds) and those from this work with constant accretion luminosity and suppressed chromospheric emission <100eV (filled circles). See section 3.1 for details.

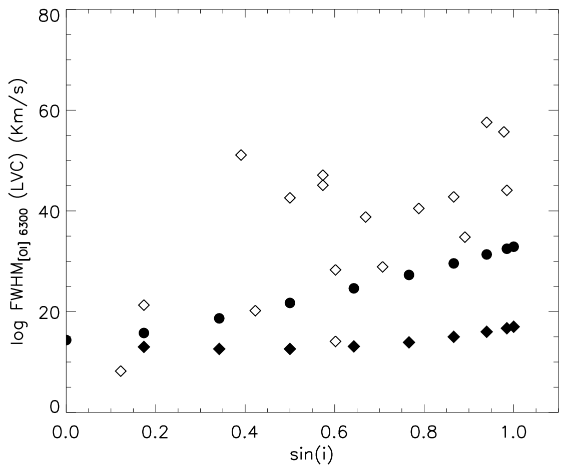


**Figure 3.** FWHM versus sine of the disk inclination from Rigliaco et al. (2013) (empty diamonds) compared to the model predictions for the $L_X = 2 \times 10^{30}$ erg/sec model of EO10 (filled diamonds) and those from the $L_X = 2 \times 10^{30}$ erg/sec, $L_{acc} = L_{bol}$ model from this work (filled circles). All model results shown here are for a spectral resolution of R=25000. See section 3.3 for details.

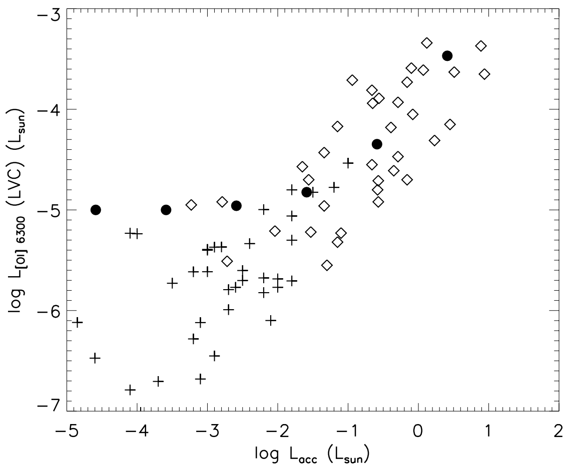


**Figure 2.** [O I] 6300 luminosity versus accretion luminosity for the Samples I and II objects from Rigliaco et al. (2013) (empty diamonds) **and the Lupus sample from Natta et al. (2014) (crosses)** compared to the model predictions from this work with constant X-ray luminosity (filled circles). Emission from the X-ray spectrum at <100eV is not suppressed in these models. See section 3.2 for details.

terms of the correlation between the emission region of the collisionally excited [OI] line at 6300A and the EUV flux reaching the wind. As the EUV luminosity is dominated by the accretion luminosity of the YSO, we show this point here by running a set of models of constant X-ray luminosity ($L_X = 2 \times 10^{30}$erg/sec) and vary only the accretion luminosity, $L_{acc} = a \times L_{bol}$, over a range of a from 1 to $10^{-5}$. The results are shown in Figure 2, where the filled circles show our models and the empty symbols the observational results of Rigliaco et al (2013). It is clear from the figure that the observed correlation is reproduced for a *constant* X-ray luminosity, and by varying only the input accretion luminosity.

Both the **Rigliaco et al. (2013)** observations and the models **seem to** show that the correlation flattens as the accretion luminosity (i.e. the UV flux reaching the wind) decreases. **In the models** this is due to the [OI] 6300 line luminosity reaching the floor value set by the X-ray illumination.

**However, Figure 2 also includes the observational sample in the Lupus star forming region from Natta et al. (2014), represented by the crosses. These data extends to much lower accretion luminosities and includes mostly late M stars with masses typically around 0.2 $M_\odot$, which is the median of their sample. The Lupus data does not show a flattening in the correlation. It is important to note at this point that our models are not appropriate for a comparison at such low masses, as they were computed for a stellar mass of 0.7 $M_\odot$ (note that only 7 out of 44 stars in the Natta et al., 2014, sample have masses larger than 0.5 $M_\odot$). The X-ray properties of such low mass stars are also not very well known. A recent attempt at characterisation of the X-ray properties in the TW Hya region by Kastner et al. (2016), found that log ($L_X/L_{bol}$) decreases for stars with spectral type M4 or later, and its distribution broadens. This study, while suffering from poor statistics for stars later than M3, also showed that the later type stars had more long-lived discs, probably due to their less efficient X-ray irradiation. A new modeling campaign to cover this new parameter space is under way and will be the focus of a future work.**

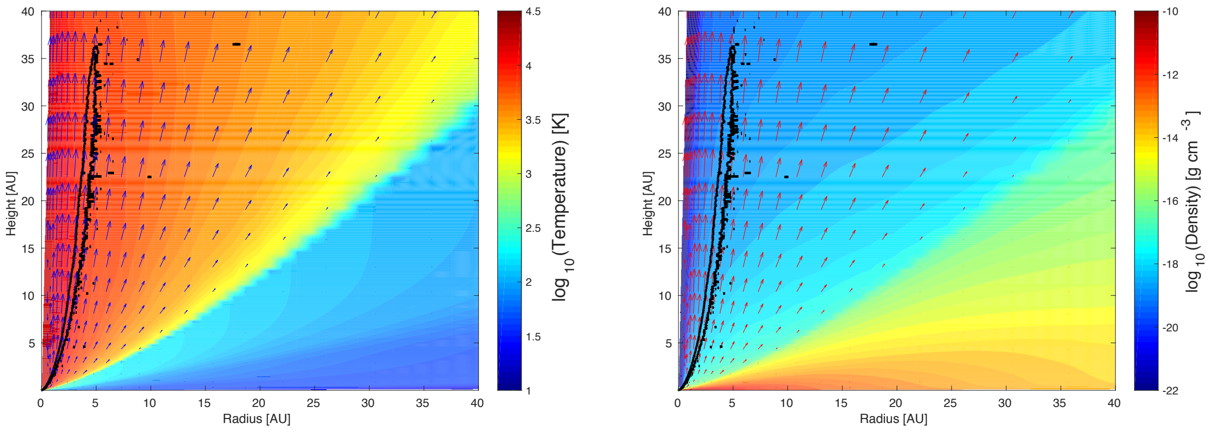


**Figure 4.** Temperature (left) and density (right) maps showing the location of the 85% emission region of the OI 6300 line (black contour). The velocity field is represented by the red arrows. Plotted is the model with $L_X = 2 \times 10^{30}$ erg/sec, $L_{acc} = L_{bol}$.

### 3.3 The FWHM of the [OI]6300: a consequence of the emission region

A further discrepancy between the model predictions of EO10 and the observational results of Rigliaco et al. (2013) are the much lower FWHM of [OI]6300 predicted by the models (filled diamonds in Figure 3) compared to the observations (empty symbols in Fugure 3). As listed in Table 2, the FWHM of the [OI] 6300 line predicted in our new models (e.g. $L_X = 2 \times 10^{30}$ erg/sec and $L_{acc} = L_{bol}$, filled circles in Figure 3) have broader FWHM, which are better in agreement with the observations. The reason for this is that the emission region of the [OI] 6300 line in our new models extends to about 35 AU above the disc (Left panel in Figure 4), compared to only up to 15AU in the models of EO10 (see their Figure 3). The [OI] 6300 line thus samples a wider range of wind velocities, which naturally results in a broader spectral profile. The corresponding line profiles are shown in Figure 6 for 10 inclinations between 0 and 90 degrees and for R=25,000 resolution (similar to the data used by Rigliaco et al. 2013) and R=50,000 (which is more representative of future work).

We stress that the underlying wind model is the same as that of EO10, the difference in the extension of the [OI]6300 line emission region is purely driven by the presence of the extra accretion luminosity component which is more efficient at heating the wind to the temperatures required to produce the [OI]6300 line in the wind at higher vertical distances above the disc.

**We note however that the FWHM values of the new models are still somewhat narrower than the observational data. The Natta et al. (2014) sample in Lupus (not shown in this plot) have on average still broader profiles, with a median FWHM of 55.5Km/s. New observational data at higher spectral resolution is needed to determine the exact spectral profile of these lines.**

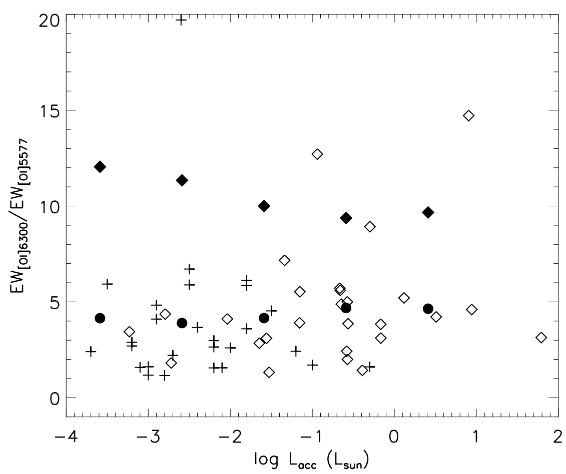


**Figure 5.** EW [OI] 6300A/EW [OI] 5577 A versus accretion luminosity for the observational data of Rigliaco et al. (2013) (empty diamonds) and Natta et al. (2014) (crosses), compared to the model predictions of this work with (filled diamonds) and without (filled circles) neutral hydrogen collision contributions to the [OI] 5577A line. See section 3.4 for details.

### 3.4 A thermal origin for the [OI] 6300: the [OI] 6300/ [OI] 5577 ratio

Perhaps the strongest doubts that the [OI] 6300 may not have a thermal origin were cast by Rigliaco et al (2013) on the basis of their observational mesurements of the [OI]6300/[OI]5577 line ratio in their sample of YSOs. Figure 5 shows that the measurements (empty symbols) scatter around a ratio of about 5, while the models of EO10 (filled diamonds) show significantly higher ratios between 7 and 10, in clear disagreement with the observations. **The empty diamonds and the crosses represent, respectively, the data from Rigliaco et al. (2013) and Natta et al. (2014).** This discrepancy led Rigliaco et al. (2013) to favour a non-thermal origin for the formation of the [OI] 6300 line. However, as was already discussed by EO10, the luminosity of the [OI]5577 line calculated from the mod-

| $L_X$ [$2E30erg/sec$] | <100eV suppressed | $L_{acc}$ [$L_{bol}$] | $L_{[OI]63000}$ [$L_\odot$] | $L_{[OI]5577}$ [$L_\odot$] |
|---|---|---|---|---|
| 1.0 | yes | 10 | 2.9e-4 | > 3.0e-5 |
| 1.0 | yes | 1 | 3.7e-5 | >3.8e-6 |
| 1e-1 | yes | 1 | 1.2e-5 | >2.3e-6 |
| 1e-2 | yes | 1 | 1.1e-5 | >2.0e-6 |
| 1.0 | yes | 1e-1 | 1.2e-5 | > 7.0e-7 |
| 1.0 | yes | 1e-2 | 8.3e-6 | > 3.6e-7 |
| 1.0 | yes | 1e-3 | 7.3e-6 | > 2.3e-7 |
| 1.0 | yes | 1e-4 | 6.2e-6 | > 2.1e-7 |
| 1.0 | no | 10 | 3.4e-4 | >4.e-5 |
| 1.0 | no | 1 | 4.5e-5 | >4.8e-6 |
| 1.0 | no | 1e-1 | 1.5e-5 | >1.5e-6 |
| 1.0 | no | 1e-2 | 1.1e-5 | >9.7e-7 |
| 1.0 | no | 1e-3 | 1.0e-5 | >8.3e-7 |
| 1.0 | no | 1e-4 | 1.0e-5 | >8.2e-7 |
| 1.0 | yes | 1 | >2.2e-5 | >4.7e-6 |
| 1.0 | yes | 1e-1 | >5.4e-6 | >1.3e-6 |
| 1.0 | yes | 1e-2 | >3.7e-6 | >9.5e-7 |
| 1.0 | yes | 1e-3 | >3.4e-6 | > 8.2e-7 |

**Table 1.** Summary of models and corresponding line luminosity predictions. See text for detail.

| inclination [degrees] | $FWHM_{25}$ [km s$^{-1}$] | $v^{25}_{peak}$ [km s$^{-1}$] | $FWHM_{50}$ [km s$^{-1}$] | $v^{50}_{peak}$ [km s$^{-1}$] |
|---|---|---|---|---|
| 0 | 14.36 | -2.1 | 8.97 | -1.6 |
| 10 | 15.76 | -2.6 | 11.25 | -2.9 |
| 20 | 18.67 | -3.6 | 14.82 | -4.4 |
| 30 | 21.73 | -4.6 | 18.32 | -5.9 |
| 40 | 24.63 | -5.1 | 21.62 | -6.6 |
| 50 | 27.29 | -5.1 | 24.63 | -6.9 |
| 60 | 29.58 | -4.4 | 27.25 | -6.3 |
| 70 | 31.36 | -3.4 | 29.33 | -6.1 |
| 80 | 32.49 | -1.9 | 30.72 | -5.1 |
| 90 | 32.89 | 0.0 | 31.38 | 0.0 |

**Table 2.** Velocity at the peak and full-width-half- maximum (FWHM) of the [OI] 6300 line for the $L_X = 2 \times 10^{30}$ erg/sec, $L_{acc} = L_{bol}$ model from this work as a function of disc inclination. The quantities were calculated for spectral resolutions of 25000 and 50000.

els is only a lower limit. Both [OI]6300 and [OI]5577 can be excited by collisions with electrons or neutral hydrogen atoms, however in the literature no neutral hydrogen collisional strengths are available for the [OI]5577 line, which is then necessarily underestimated, while the [OI]6300 predictions include both contributions from electron and neutral hydrogen collision.

To illustrate this point better we have perfomed calculations where we turn off neutral hydrogen collisions for the [OI]6300, so that both [OI]6300 and [OI]5577 only include collisions with electrons. These results are also shown in Figure 5 where the predictions from the electron collision only calculations are shown as filled circles. These new calculations are consistent with the observational measurements, implying also that hydrogen collision strengths must contribute in a comparable fashion to the fluxes of both the [OI]6300 and the [OI]5577 lines.

## 4 CONCLUSIONS

We have revisited the question of the origin of the low velocity component (LVC) of the blueshifted [OI] line at 6300A. Our new models suggest that this line is produced by collisional excitation of neutral Oxygen by free electrons and neutral hydrogen atoms in the quasi-neutral X-ray photoevaporative winds of young stellar objects up to approximately 1 $M_\odot$. Our current models are not relevant to higher mass Herbig-type stars as the photoevaporative wind structure is likely to change due to the fact that these objects have much lower (or absent) X-ray luminosities compared to their solar-like counterparts.

Our models show that while the wind structure is driven by X-ray radiation (0.1 keV< $E$ <1keV) reaching the bound atmosphere of a protoplanetary disc, the size of the emitting region of optical forbidden lines is determined by the EUV (13.6 eV< $E$ <100eV) photons reaching the wind. The wind is optically thick to EUV radiation, which thus cannot reach the bound disc atmosphere at all. In fact EUV photons penetrate into and heat only a thin vertically extended (up to about 37 AU) region of the wind above the inner disc (<5AU). The luminosity of the [OI] 6300 line and, in fact, of all forbidden lines that have an exponential temperature dependence (due to the Boltzmann term in their emissivity), are strongly weighted to the hottest regions, where neutral hydrogen is still abundant. This is shown in the left panel of Figure 4. This means that the line luminosities scale with the size of the wind region that can be heated by the EUV to the appropriate temperature. From this it follows, as confirmed by our models, that the luminosity of optical forbidden lines is correlated with the accretion luminosity of the YSO.

As a consequence the luminosity of lines like [OI] 6300 cannot be used to measure wind properties, such as mass loss rate, as their production is not due to the same radiation that causes the photoevaporation of the disc atmosphere. Nevertheless the blueshifted low velocity components detected by (e.g.) Hartigan et al. (1995), Rigliaco et al. (2013) and Natta et al. (2014) are a clear tell-tale sign of a disc wind. High spectral resolution observations of these lines, particularly in combination, remain an important diagnostic tool of mass loss processes from disc atmospheres.

## 5 ACKNOWLEDGEMENTS

We thank an anonymous referee for helpful comments on the first version of this paper. We thank Elisabetta Rigliaco for making electronic versions of their data available to us and for the useful discussion. JEO acknowledges support by NASA through Hubble Fellowship grant HST-HF2-51346.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555.

## REFERENCES

Alexander, R. D., Clarke, C. J., & Pringle, J. E. 2006, MNRAS, 369, 216
Alexander, R. D. 2008, MNRAS, 391, L64

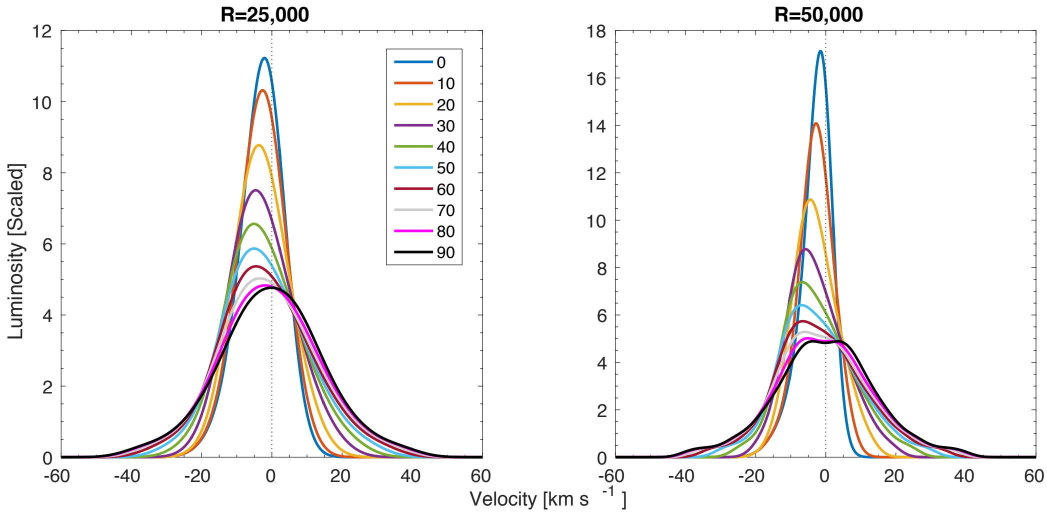


**Figure 6.** [OI] 6300 line profiles from our high resolution hydrodynamical simulations. See text for detailed. The left panel shows line profiles computed with a spectral resolution of 25,000 whereas the right panel is at 50,000. Each line indicates a different viewing inclination, where the inclination is indicated in the legend in degrees.

Asplund, M., Grevesse, N., & Sauval, A. J. 2005, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, 336, 25
Ercolano, B., Barlow, M. J., Storey, P. J., & Liu, X.-W. 2003, MNRAS, 340, 1136
Ercolano, B., Barlow, M. J., & Storey, P. J. 2005, MNRAS, 362, 1038
Ercolano, B., & Storey, P. J. 2006, MNRAS, 372, 1875
Ercolano, B., Drake, J. J., Raymond, J. C., & Clarke, C. C. 2008a, ApJ, 688, 398
Ercolano, B., Young, P. R., Drake, J. J., & Raymond, J. C. 2008b, ApJS, 175, 534-542
Ercolano, B., Clarke, C. J., & Drake, J. J. 2009a, ApJ, 699, 1639
Ercolano, B., & Owen, J. E. 2010, MNRAS, 406, 1553
Ercolano, B., & Rosotti, G. 2015, MNRAS, 450, 3008
Gorti, U., Dullemond, C. P., & Hollenbach, D. 2009, ApJ, 705, 1237
Hartigan, P., Edwards, S., & Ghandour, L. 1995, ApJ, 452, 736
Hayes, J. C., Norman, M. L., Fiedler, R. A., et al. 2006, ApJS, 165, 188
Kashyap, V., & Drake, J. J. 2000, Bulletin of the Astronomical Society of India, 28, 475
Landi, E., Del Zanna, G., Young, P. R., et al. 2006, ApJS, 162, 261
Maggio, A., Flaccomio, E., Favata, F., et al. 2007, ApJ, 660, 1462
Mohanty, S., Jayawardhana, R., & Basri, G. 2005, ApJ, 626, 498
Natta, A., Testi, L., Alcalá, J. M., et al. 2014, A&A, 569, A5
Owen, J. E., Ercolano, B., Clarke, C. J., & Alexander, R. D. 2010, MNRAS, 401, 1415
Owen, J. E., Ercolano, B., & Clarke, C. J. 2011, MNRAS, 412, 13
Owen, J. E., Clarke, C. J., & Ercolano, B. 2012, MNRAS, 422, 1880
Owen, J. E., & Wu, Y. 2016, ApJ, 817, 107
Pascucci, I., Hollenbach, D., Najita, J., et al. 2007, ApJ, 663, 383
Pascucci, I., Sterzik, M., Alexander, R. D., et al. 2011, ApJ, 736, 13
Rigliaco, E., Pascucci, I., Gorti, U., Edwards, S., & Hollenbach, D. 2013, ApJ, 772, 60
Sanz-Forcada, J., Brickhouse, N. S., & Dupree, A. K. 2002, ApJ, 570, 799
Stone, J. M., & Norman, M. L. 1992a, ApJS, 80, 753
Stone, J. M., & Norman, M. L. 1992b, ApJS, 80, 791
Stone, J. M., Mihalas, D., & Norman, M. L. 1992c, ApJS, 80, 819
Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, ApJ, 465, 487
Verner, D. A., & Yakovlev, D. G. 1995, AAPS, 109
White, R. J., & Hillenbrand, L. A. 2004, ApJ, 616, 998