Project A1:

Solids and gas evolution in disks: observational constraints

Authors:

PI:	L. Testi (ESO)
Co-I:	B. Ercolano (LMU), T. Preibisch (LMU), T. Henning (MPIA), E. van Dishoeck (Leiden, MPE)
Collaborations:	H. Baobab Liu (ESO), J.M. Carpenter (ALMA), G. Guidi (INAF/UniFi) A. Miotello (Leiden), I. Pascucci (Arizona), A. Natta (DIAS/INAF), M. Tazzari (IoA), J.P. Williams (Hawaii), Hsi-Wei Yen (ESO)

Requested positions: 2 PhD students

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 VLA observations. We will firmly characterize the level of grain growth and the gas content as traced by CO and isotopologues 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.

1. State of the art and preliminary work

The aim of this project is to provide an observational characterization of the dust and molecular gas (as traced by CO and its isotopologues) in transition disks as part of the global population of protoplanetary disks in nearby star forming regions.

Transition Disks are generally observationally defined based on the observed Spectral Energy Distribution (SED) and disk sub-mm morphology which are characteristic of disks with an inner region with low dust opacity. There is still uncertainty on their relation to disk evolution and planet formation, but are generally thought to be a transition phase that primordial full disks undergo as they are dissipated (see e.g. Williams & Cieza 2011). In recent years the brightest disks with the largest holes have started to be characterized with high angular resolution submm continuum and spectral line observations. Pre-ALMA observations have been used to quantify the dust surface density drop required to explain the observed inner cavities (e.g. Andrews et al. 2011), and ALMA is now allowing a more detailed study of the molecular gas content (e.g. van der Marel et al. 2015). The relationship between TDs and dust evolution and planet formation has also started to be investigated, but with very limited studies so far (e.g. Pinilla et al. 2014, Sallum et al. 2015). These initial studies have provided fundamental insights on the properties of TDs, but a systematic comparative study with the properties of the global population of disks in different star forming regions is lacking.

A systematic assessment of the properties and evolution of dust and gas in TDs as compared with the rest of the disk population is required to constrain the nature of TDs and their relation to the global disk evolution and planet formation process. Four main properties are required and can now be

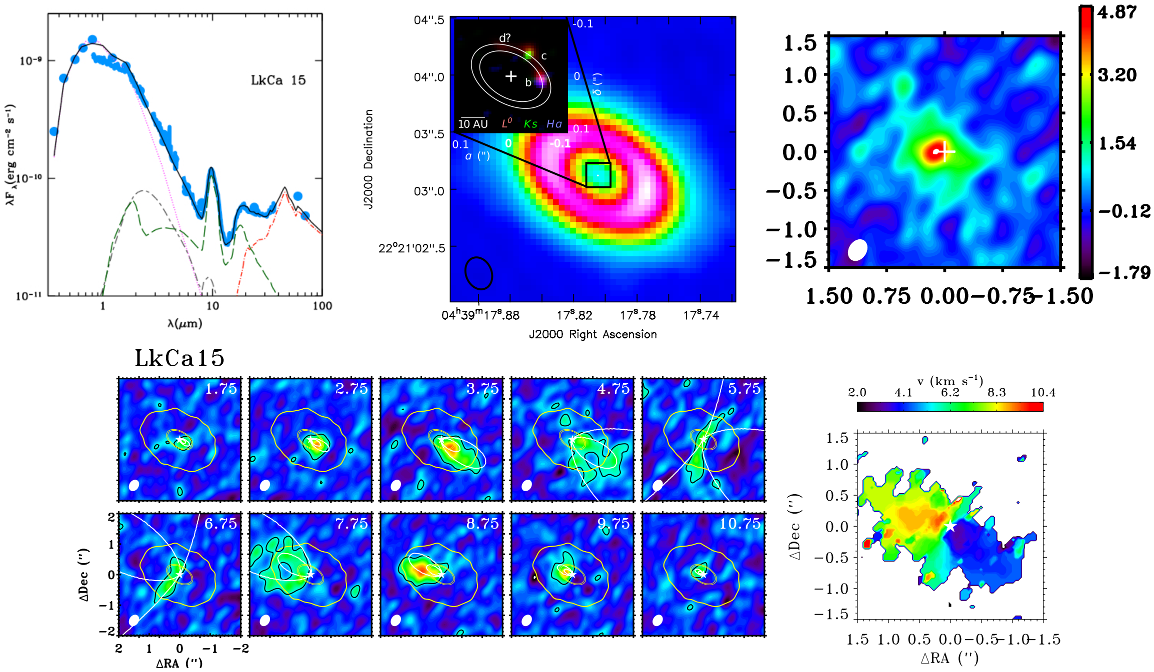

Figure 1: The LkCa15 Transition Disk. **From left to right and top to bottom:** SED of the LkCa15 system showing the characteristic dip of Transition Disks in the mid-infrared , followed by a rise at far-infrared wavelengths (Espaillat et al. 2011); ALMA dust continuum image, showing the characteristic inner hole (in this case the cavity outer radius is ~45 AU), the inset shows the location of the young planets detected in this system (Sallum et al. 2015); the ALMA observations of ^{12}CO(6-5) observations show the presence of warm gas inside the cavity (van der Marel et al. 2015).

constrained observationally: the dust properties and distribution, the gas properties and distribution, the wind and accretion properties, and the presence and properties of planets. These properties are related to the evolution of disks and the formation of planets: dust grains are expected to grow to pebbles and planetesimals and eventually form the cores of planets; the disk gas content is the reservoire out of which planetary atmospheres are formed, its evolution is linked to the interplay between planet formation and disk dispersal; accretion onto the central star and the wind properties are key observables to compare with disk dissipation models; the effects of planets on the disk, once they are formed, can profoundly influence the future ability of the disk to form planets and its dissipation.

Detailed studies of few TDs exist on all the aspects above (see Fig. 1 for the case of LkCa15, the only TD with directly imaged planets inside the inner cavity), but it is now possible to explore the properties of TDs in the broader context of the demographics of planet forming disks as a function of age and as a function of the properties of the central star.

In the following four subsections, we summarize the state-of-the-art of our observational constraints on the four main properties outlined above and point out one key question in each area that we will address as part of this project and in collaboration with the rest of the RU teams.

1.1 Dust properties and distribution

The properties of the dust distribution is the main observable quantity that sets the TDs class apart form the rest of the disk population. The presence of a hole in the dust distribution can be inferred from the SED, and the hole size roughly constrained through modeling, but only direct imaging at (sub-)millimetre imaging. 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), in other cases there is compelling evidence for more massive planets affecting the disk dust and gas distribution (Perez et al. 2016; Isella et al. 2016).

As of today, relatively few and bright (massive) disks have direct measurements of the inner hole from sub-mm imaging and even fewer constraints on the dust properties in the disk. The most comprehensive catalog of candidate TDs, based on SED modeling, is that of van der Marel et al. (2016), which includes over 130 high probability TDs in nearby star forming regions. Nevertheless, for the small fraction of disks with inner cavity measurements from mm interferometry the correlation between the inferred hole sizes from the SED and the sizes from direct imaging show a large dispersion (see Figure 2). Using the scant and limited quality data available so far, Pinilla et al. (2014) showed a potential correlation between the average dust properties in TDs and the size of the inner cavity. This result is consistent with a scenario in which inside-out planet formation consumes the large grains in the inner regions of the disk to form planets, and, as the disk is progressively evacuated by planets and photoevaporation, the average dust properties are dominated by smaller grains in the outer regions of the system. Nevertheless, there are still large uncertainties and biases on the measurements of TDs hole sizes and on the dust properties. In addition, there is marginal evidence for the dust properties to vary in different star forming regions (see Figure 2, bottom panels), hence to properly understand TDs evolution it is necessary to compare with the dust properties of the full disk populations in the same star forming regions.

Q1: *Can we trace the evolution of the grain size distribution in full disks and TDs as disk dissipation and planet formation progress?*

1.2 Gas properties

Most of the primordial disk mass is in the form of molecular gas. As cold H_2 is not directly observable due to the lack of a permanent dipole moment, the gaseous component of the disks can only be traced by the much less abundant molecules. CO is the prime tracer of molecular gas in planet forming disks. The few TDs with detailed gas observations from ALMA show that in many cases the inner cavities are not empty, but contain warm gas, while the outer disk is rich in cold molecular gas, as primordial disks (van der Marel et al. 2015). Nevertheless, our current understanding is not yet clear-cut: quantifying the amount of gas inside the inner hole and in the outer disk are essential to provide constraints on the ability of disks to form and interact with planets and for the disk dissipation models.

The characterization of the gas contents of disks during their evolution is an area that is being profoundly transformed by ALMA: for the first time we have the sensitivity to study large samples. Our

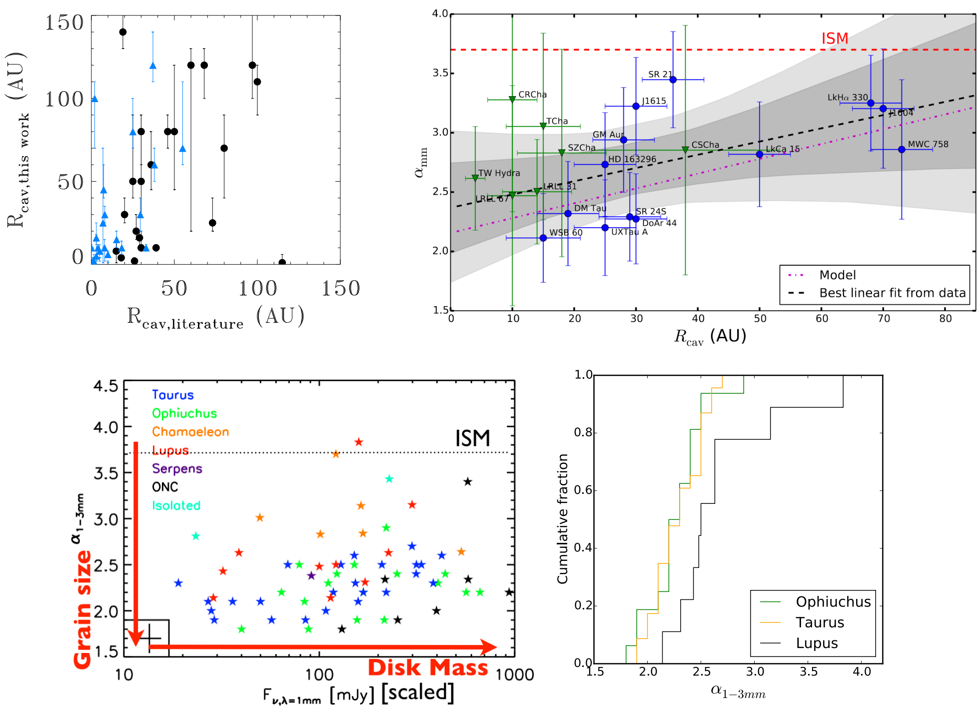

Figure 2: **Top left:** TDs hole sizes as derived from SED fitting and direct imaging (black points only; adapted from van der Marel et al. 2016a). **Top right:** relationship between TDs hole radius and mm spectral index (as a proxy of grain growth in disks, large grains correspond to small values of α; adapted from Pinilla et al. 2014). **Bottom left:** compilation of pre-ALMA photometric estimates of grain growth in disks from millimetre spectral indices (adapted from Testi et al. 2014). **Bottom right:** distributions of the mm spectral indices for objects in the young Taurus/Ophiuchus regions (yellow/green lines, data from Ricci et al. 2010ab), and the slightly more evolved Lupus region (black line, data from Lommen et al. 2007 and Ubach et al. 2012).

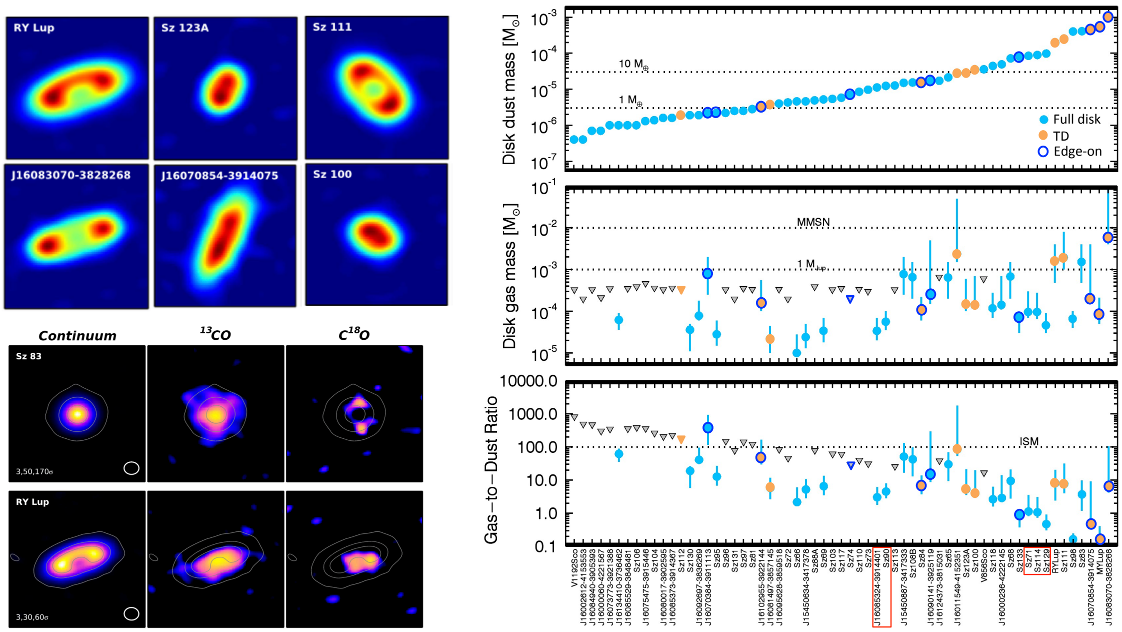

Figure 3: **Top left 6 panels:** ALMA 890 μm continuum images of six of the TDs in Lupus (LADS survey; adapted from Ansdell et al. 2016). **Bottom left panels:** Comparison of the LADS continuum (left colormap and contours in all panels) and ^{13}CO (center colormaps) and C^{18}O (right colormaps) for a full disk (top) and a TD (bottom), note that the C^{18}O emission fills the inner hole in the TD (adapted from Ansdell et al. 2016). **Right panels:** From top to bottom: dust disk mass, gas disk mass (as derived from CO modeling), gas to dust ratio; TDs are shown as orange circles, while full disks are blue symbols, grey triangles are upper limits (adapted from Miotello et al. 2016).

group made a key contribution in this area in 2016 with the results of the Lupus ALMA Disks Survey (Ansdell et at. 2016): for the first time an almost complete and unbiased sample of planet forming disks in continuum and gas was used to estimate the demographics of disk gas properties in an entire star forming region for TDs and full disks. The picture that we derive from an accurate analysis combining dust and ^{13}CO/C^{18}O(3-2) emission and detailed modelling of the gas (including selective photodissociation and freezing out) is intriguing in many respects: the gas-to-dust ratios that we derive from modeling the CO are lower by one or two orders of magnitudes as compared to expectations; there is no significant difference in this result between TDs and normal disks (see Fig. 3; Ansdell et al. 2016; Miotello et al. 2016). There are cases in which full disks show an apparent hole in the CO isotopologues (e.g. see the example in Fig. 3), most likely this is the effect of continuum optical depth suppressing the line emission (see also Isella et al. 2016), which emphasizes the importance of a detailed modeling of the disk emission to extract the gas properties.

The LADS results are tanatalizing, but they need to be followed up to understand the caused of the low gas-to-dust ratio as measured from the CO isotopologues.

Two other surveys of disks in nearby star forming regions have been completed (Upper Sco, Barenfeld et al. 2016, and Chamaeleon I, Pascucci et al. 2016), but have not yet been fully analysed for the molecular gas content. ALMA data for two additional surveys of RCrA and σOri have been obtained by our group, the data is expected to be delivered to us in Winter 2016-2017. A complete survey of the Ophiuchus disk population is being carried out by another group, we expect the data to become publicly available in mid-2018.

Q2: *can we trace the evolution of molecular gas as a function of disk evolution and in TDs as disks are dissipated and planet formation is occurring?*

1.3 The disk-star-accretion connection

Fill this section?

1.4 Presence and properties of planets

Observational studies and simulations of TDs suggest that the presence of planetary-mass companions within the inner hole may be common, and indeed, in a few cases of TDs there are clear observational indications (e.g. Reggiani et al. 2014; Sallum et al. 2015, see also 1; van der Marel 2016b). Nevertheless, as outlined above, ALMA is now revolutionizing our view of FULL disks as it allows for the first time to resolve in exquisite detail the solids and distribution and reveal the process of planet formation as it unfolds.

High angular resolution continuum observations of protoplanetary full disks with ALMA reveal a variety of small scale structures. The most famous and dramatic example is the ring system around the young star HL Tau (ALMA Partnership 2015), but many more are being published by various groups from the PI-science observations of dust distributions in disks at 1.3mm and/or 890μm at 0.05-0.1 arcsec angular scales (e.g. TW Hya, Andrews et al. 2016; HD163296, Isella et al. 2016; Elias 2–27, Perez et al. 2016; among many others). The variety of single wavelength millimetre continuum morphologies observed so far is very broad: dark rings, with variable depth and location, and spiral structures with different contrasts and threads, with and without inner rings. Particularly relevant in this context are the observations of Isella et al. (2016), who showed that the gaps observed in the dust distribution are also associated with depressions in the gas surface density, indicating the presence of relatively large planets.

A key feature, first suggested by the observations of HL Tau, seems to be that planet formation in the outer disk (R$\geq$10-20 AU) can occur very early in the disk life, much earlier than the typical 2-3 Myr lifetime. This could be the result of planet formation via gravitational instabilities in massive young disks. Massive planets (M$\geq 1-5$ M_{Jup}) formed by gravitational instabilities in the outer disk should be able to quickly open gaps in the disk leading to some of the observed features. More specifically, recent simulations on embedded planets in dusty disks, suggest that the minimum planetary mass needed to carve a gap in both dust and gas is as low as 1 to a few M_{Jup}, depending on the parameters of the system (Dipierro et al. 2016, see Fig. 1). Young planets down to $\sim$1 M_{Jup} should then be observable through the gaps they open in the disk using state-of-the-art thermal and near infrared high contrast imaging instruments at large telescopes. We have initiated a survey program using LBT/LBTI and VLT/SPHERE to survey for planetary mass companions in planet forming disks that show dust and gas gaps and holes with ALMA high angular resolution observations. The initial results demonstrate the possibility to achieve the goal of detecting Jupiter-mass companions in the outer disk.

Q4: *are $\geq$1 M_{Jup} planets common in planet forming disks and which is their relationship with the observed distribution of dust and gas in full disks and TDs?*

1.5 Project-related publications

[Text]

2. Objectives and work programme

2.1 Anticipated total duration of the project

3 years

2.2 Objectives

Kees to Leonardo: How are objectives O1, O2, O3 and O4 related to questions Q1, Q2, Q3 and Q4? Note that O and Q look almost identical, so it is easy to confuse them.

The objective of this project is to provide the observational constraints on the dust and gas properties in disks based on ALMA observations.

Kees to Leonardo: Maybe add a sentence like "The aim is to put TDs into context of the bigger picture, and find out if there is an evolutionary link between TDs and ordinary (full) disks." or something like this. Reason: This is a RU on TDs, so we must avoid that the referees wonder why you wish to study sources like HD 163296 or HL Tau.

This project will produce:

O1 an homogeneous analysis of the ALMA surveys for the dust mass and surface density properties of disks in star forming regions in the Solar neighbourhood. We aim in particular at determining the timeline for the evolution of the total solid mass and distribution as disks evolve during the planet formation phase (1-5 Myrs), comparing the properties of full disks with TDs;

O2 an analysis of the overall level of grain growth and of the radial and vertical stratification of grain properties in disks. We will provide constraints on the dust evolution and transport models as a function of age and mass of the central star and morphology (full vs. TD) of the disks;

O3 an homogeneous analysis of the CO-gas content in disks in nearby star forming regions. The key goal will be to understand whether the apparent CO-emission deficit observed in disks at $\sim$3 Myr is due to an evolution of the gas-to-mass ratio or due to other (e.g. chemical) effects, comparing the properties of full disks with TDs;

O4 a detailed analysis of a selected sub-sample of protoplanetary disks observed by ALMA at high angular resolution to characterize the properties of gaps (in full disks) and holes (in TDs) in the dust and gas surface densities. We will initially focus on a subset of disks for which ALMA and high contrast infrared imaging are both available or are being collected as part of approved programmes.

These objectives are ambitious, but achievable with the available or planned observations, expertise and tools available to our group, as we detail in the section below.

2.3 Datasets for the proposed project

To achieve the objectives **O1**-**O4** listed in paragraph 2.2 it is necessary to analyse a diverse set of ALMA observations. The ALMA data that we intend to use for this project comes either from (completed or scheduled) projects for which one of the team members is Principal Investigator, or from high-priority scheduled projects that will be completely observed in 2017 and for which the data will be publicly available in the course of 2018 through the ALMA Archive.

ALMA Data for objectives O1, O2, and O3.

In Table 1 we summarize the datasets already available for this projects and those that will be observed in the first half of 2017 (as part of ALMA Cycle 4), and will become public in the ALMA Archive by the end of 2018. The listed datasets will be sufficient for fully achieving **O1** and **O3**. The approved programmes and data will also allow us to obtain an initial set of results for **O2**, also including a comparison with previously published surveys (see Ricci et al. 2010ab and Testi et al. 2014). The available datasets are also shown in graphical form in Fig. 4, where we also mark with light symbols the objects for which XShooter spectra are available (which will be exploited in connection with project A2).

Table 1: ALMA disk surveys that will be used to address objectives **O1**, **O2**, and **O3**. For each star forming region we list the age, number of disks, range of stellar masses, objective for which they will be used, principal investigator (in bold face if collaborator to this project), status of the observations and expected data availability. All surveys have angular resolution in the range 0.2-0.5 arcseconds. The surveys useful for objectives **O1** and **O3** cover 1.3 or 0.89 mm continuum and CO and/or isotopes. The follow-up surveys useful for **O2** target the detection of the 3 mm continuum emission.

Region	age (Myr)	number of disks	star mass range ($M_\odot$)	Objectives O1	O2	O3	PI	status and availability
ρ-Ophiuchi	~ 1	~ 100	$\sim$0.1-2	✓		✓	L. Cieza	Schedued: Spring 2017
Corona Australis	~ 1	43	$\sim$0.2-2	✓		✓	**H. Baobab Liu**	Available, end 2016
Lupus	~ 2	89	$\sim$0.1-2	✓		✓	**J. Williams**	Available
		98	$\sim$0.1-2		✓	✓	**J. Williams**	Observed, exp. Jan 2017
		36	$\sim$0.1-2		✓		**M. Tazzari**	Available, end 2016
Chamaeleon I	~ 3	93	$\sim$0.05-2	✓		✓	**I. Pascucci**	Available
σ-Orionis	~ 4	34	$\sim$0.5-2	✓		✓	**J. Williams**	Observed, exp. Jan 2017
Upper Scorpius	~ 5	106	$\sim$0.15-1.7	✓		✓	**J. Carpenter**	Available
	~ 5	24	$\sim$0.15-1.7		✓		L. Ricci	Observed; exp. mid 2017

Additional observations may be requested as part of ALMA Cycle 5 (2017/2018) or Cycle 6 (2018/2019) to expand the ALMA 2-3 mm surveys. We see little risk in obtaining this additional data given the limited amount of time required, the strong science case, also based on the results of the complete ALMA surveys at 1.3 and 0.89 mm, and the fact that our team has a proven track record in obtaining ALMA data for this type of projects.

ALMA Data for objective O4.

Objective O4 requires a combination of high angular resolution and high sensitivity data, to be able to resolve the gaps and holes and to detect at sufficient signal to noise ratio. There are several datasets either in the ALMA archive or scheduled to be observed that can be used. We will initially focus on three objects, in different evolutionary stages, for which detailed ALMA and VLA observations are available and for which we have acquired, or are in the process of acquiring, complementary high-contrast infrared observations: the young disk in HL Tau, the full disk HD163296, and the TD around CQ Tau.

All three objects already have, or we expect to receive in early 2017 from ALMA and the VLA, multi-wavelength continuum observations that allow us to trace the dust properties at different disk locations. Our own and archival datasets will also provide observations of the molecular gas in the three objects. The initial modeling results that we aim to verify is that these three disks are in different stages of the planet formation process: HL Tau contains rocky cores of planets that can effectively create gaps in the dust, but not in the gas surface density; HD163296 has sub-jupiter planets able to open gaps of varying depth in the dust and gas distributions; CQ Tau contains large planets and is in an advanced phase of disk dissipation.

A summary of the available data on these three disks is shown in Figure 5, including the complementary high-contrast imaging data that our team is acquiring to complement this project. In addition to these three disks, for which our team has direct access to available or planned multi-wavelength ALMA and VLA observations, we are in the process of securing high-contrast NIR imaging and high-resolution ALMA observations for an extended sample of five additional disks (2 TDs and 3 full disks).

2.4 Tools for data analysis

In the last few years, our group has been developing and testing

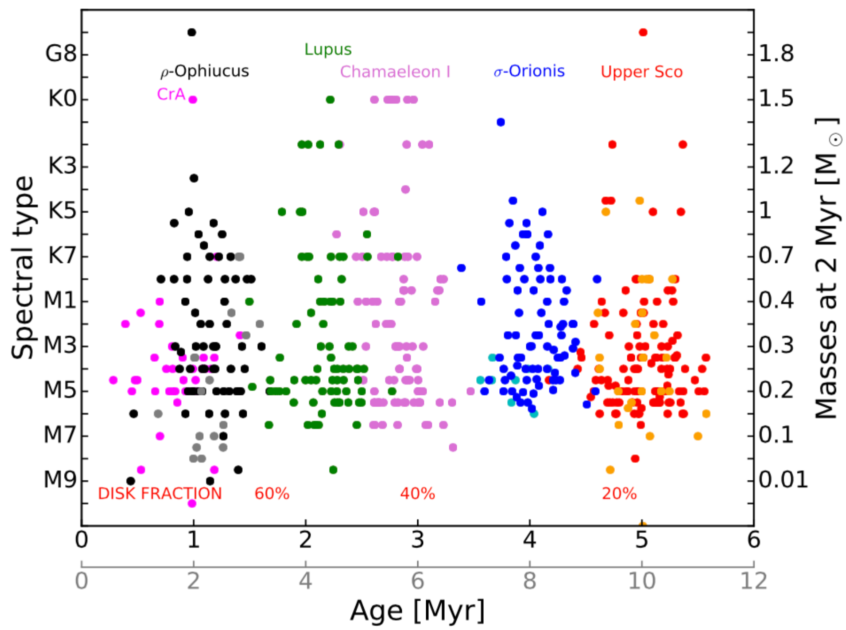

Figure 4: Samples for which ALMA observations of disks will be available for this project. The spectral types are actual measurements; the ages are assigned randomly to each point using the mean age and age dispersion in each region.

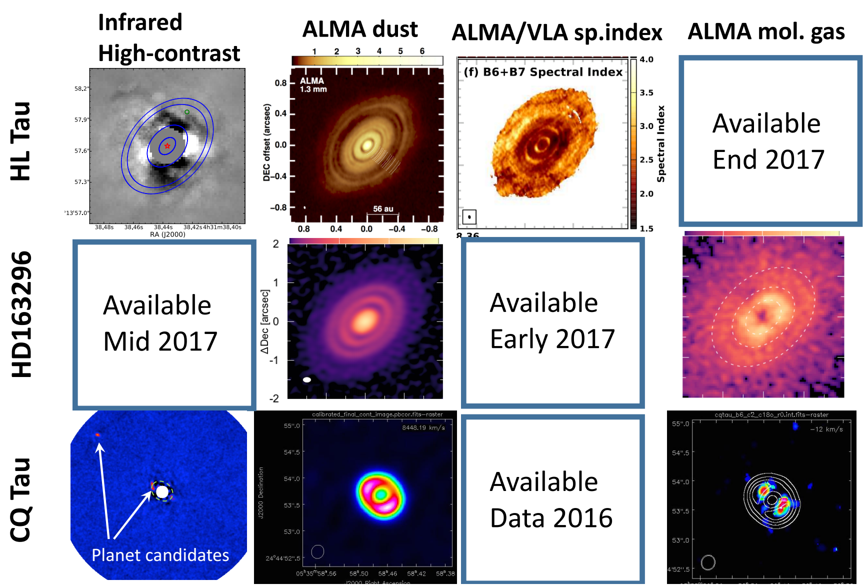

Figure 5: **From Top to Bottom:** available data for HL Tau, HD163296 and CQTau. In **each column** we show: the complementary high-contrast infrared data to search for planetary mass companions, the ALMA continuum image, the ALMA spectral index image, the molecular line integrated image. On the high contrast images we show the position of the gaps in HL Tau (Testi et al. 2015), and the position of the outer edge of the disk cavity in CQ Tau (Testi et al., in preparation); HD163296 will be observed at the Keck telescope with the high-contrast imager in Jun 2017. The ALMA continuum images are at 1.3 or 0.89 mm (ALMA Partnership et al. 2015; Isella et al. 2016; Perez et al. in preparation). New high sensitivity data from the VLA and ALMA will be used to construct the spectral index maps for HD163296 and CQ Tau (data being acquired); several ALMA programs aiming at observing the gas distribution in HL Tau, HD163296, and CQ Tau are in progress.

Dust properties and surface density as a function of radius

As part of the PhD thesis of M. Tazzari at LMU, we developed an effective analysis tool that can be used to derive the dust properties and surface density as a function of radius. The novel modeling toolkit, allows to efficiently model multi-wavelength continuum observations of disks at millimetre and radio wavelengths to self-consistently derive the disk physical parameters (including the dust surface density distribution) and the level of grain growth as a function of radius in the disk. This tool has been verified and successfully applied to observations of planet forming disks, allowing for a direct comparison with global dust evolution models in disks (Tazzari et al. 2016ab; Tazzari et al. 2017).

Disk gas masses from ALMA observations

As part of her PhD thesis at the University of Leiden, A. Miotello is developing an accurate method to measure the amount of molecular gas protoplanetary disks from CO and isotopologues millimetre observations. To overcome some of the difficulties in in deriving reliable gas surface densities from observations of line intensities, the method relies on a detailed chemical-physical computation of the disk dust and gas structure, including selective effects on the CO isotopologues. Miotello et al. (2016) have used this method to derive measurements of the molecular gas content in disks using a combination of line luminosities in different CO isotopologues, improving on the method of Williams & Best (2014).

The application of this method to the Lupus ALMA disks survey (Miotello et al. 2017, see also Fig. 3) has shown a significant inconsistency between the disk masses measured using dust or CO as tracers. This inconsistency could be related to a real deficit of the gas content in the Lupus disks, or to unexpected chemical depletion of CO and isotopologues. In collaboration with the Lupus team, and as part of the last part of A. Miotello PhD, we are exploring which of these two possibilities is correct using multi-transition CO and isotopologues data coming from approved ALMA programmes. This new analysis will be used to improve the method in the course of 2017. In collaboration with the group of J. Williams in Hawaii, we also plan to expand the method to derive gas surface densities for spatially resolved observations of gaseous disks.

2.5 Work programme including proposed research methods

Kees to Leonardo: Please add into the text something about the role of the co-Is and other RU collaborators. Thomas Henning and Ewine van Dishoeck have of course loads of exciting data from SPHERE (Thomas) and ALMA (Ewine). It would be perhaps nice to see if you can find a way to link their expertise somehow (at least a bit) into this project. And what about adding Til, since his expertise may be useful to interpret the observations? Link to project C1 perhaps? For the gas phase tracers maybe you can refer to the expertise of Paola's group and Ewine's group on the chemistry of the gas in the disk, and link to project B2?

The two PhD students hired for this project will each be responsible for one of the two main sub-project: evolution of the demographics of disk properties and evolution of the detailed physical properties of disks with embedded planets. The workplan for the two sub-projects is detailed below.

2.5.1 Evolution of the demographics of disk properties

Months 1-12

We will start with the detailed analysis of the continuum properties of the Lupus disks from the combination of the ALMA surveys at 0.89, 1.3 and 3 mm. Dust emissivity, surface density and temperature distributions are key uncertainties when deriving disk dust masses from sub-mm observations. The combination of the multi-wavelength observations of the Lupus disks will allow to greatly reduce the uncertainties. Using the modeling tool described in Sect. 2.4) we have already investigated the possibility of refining the dust mass estimates by applying a correction that depends not only on the stellar luminosity (see the attempts by Andrews et al. 2013 and van der Plas et al. 2016), but also on other parameters like the radial extent of the millimetre wave emission (Tazzari et al. 2017). These initial results need to be validated using the multi-wavelength sample, in order to check for potential systematic effects introduced by the varying dust properties (see e.g. Banzatti et al. 2011; Tazzari et al. 2016a). All the data for this analysis is available, as the data has been delivered at the end of 2016. We also expect that at the beginning of the project all Lupus datasets will be already calibrated and ready to start the analysis.

The modeling procedure is already fully developed and tested on the single wavelength Lupus data, the key result that we will obtain for each modeled disk will be: the total disk mass, the average dust properties (and possibly an indication of the dust properties as a function of radius), and the radial extent of the disk containing the bulk of the dust mass. The collaboration with M. Tazzari, will be crucial in this phase of the project and the student may spend **(some text missing here: sentence ends abruptly)** From our initial results on the Lupus 0.89 mm survey, we estimate that the we will be able to carry out this analysis to almost half of the Lupus sample ($\sim$ 35 disks). This sample contains 7-10 TDs, so we will also be in the position of addressing a first systematic assessment of the comparison of dust properties of TDs versus full disks.

During this period the student will also learn how to prepare the data from the other surveys available for this analysis. We will collect and re-process the ALMA data in a uniform way and, for all regions, we will use the methodology of Pascucci et al. (2016) to recompute the stellar parameters, as this is a more robust technique than the one used in the initial studies of Barenfeld et al. (2016) and Ansdell et al. (2016).

Single wavelength data for the dust continuum emission and stellar parameters will be available at the end of this period for the following star forming regions (on top of Lupus): Corona Australis, Chamaeleon I, σ-Orionis, Upper Scorpius. The line data will also be calibrated, but not analysed yet, at this stage.

Products:

- One publication on the dust properties and continuum masses in the Lupus cloud, including a comparison between full disks and TDs.
- ALMA proposal to extend the studies of the multi-wavelength dust properties to other regions beyond Lupus and Upper Sco
- Datasets and methods ready for the comparative analysis of different star forming regions

Months 13-24

We will develop the statistical tools to compare the dust measurements in the different regions. Different regions have different properties in terms of the stellar populations, fractions of stars with disks and completeness of the surveys. These limitations have not been taken fully into account in previous comparisons between the properties of disks in different star forming regions (e.g. Ansdell et al. 2016; Pascucci et al. 2016). To take into account the sampling and completeness biases, we will compare observational data to Monte Carlo simulations, building on and extending the methodology developed by Andrews et al. (2013).

The comparative study of the properties of the continuum emission of all star forming regions planned in this study will be completed in this phase. This will include the disks in ρ-Oph if the ALMA data will be available in time.

The database will be extended to include the molecular line maps of the disks.

Products:

- One publication on the comparative properties of dusty disks in star forming regions as a function of age, including a comparison between full disks and TDs.
- Statistical methods ready to be applied to the analysis of the gas properties

Months 25-36

The demographical analysis of the gas properties will be carried out during the third year. This analysis will be carried out as part of the collaboration with A. Miotello and J. Williams, using the methods that are currently being refined and are described in Sect. 2.4. For this analysis we will use the simplified fitting functions, rather than performing a full chemical modeling of each disk, which would be a prohibitively time consuming activity if applied to all the disks in our surveys. The fitting functions provided by Miotello et al. (2016) will be improved following the ongoing studies (as described in Sect. 2.4), in addition, as part of our collaborations, we are planning to extend the model grids for a range of the stellar photospheric parameters. These new grids will be applied to derive more accurate measurements of the gas content to be compared with the solids content in disks as a function of the evolutionary status.

Products:

- One publication on the comparative properties of the gas content in disks in star forming regions as a function of age, including a comparison between full disks and TDs.
- Investigation of the possible evolution of the overall gas-to-dust ratio in disks as a function of age, evolutionary stage and stellar parameters; with particular emphasis on determining possible population differences between full disks and TDs

2.5.2 Evolution of the detailed physical properties of disks with embedded planets

Kees to Leonardo: Perhaps the work program for this project (I assume PhD student 2) needs to a bit more detail.

Months 1-12

In this phase we will collect and reprocess the ALMA and VLA high angular resolution observations of CQ Tauri amd HD163296 (the HL Tau continuum data are already available). Expert fellows at ESO and collaborators on this project (Baobab Liu and Hsi-Wei Yen) will support this data calibration effort.

- extension of M. Tazzari tool to fit gas visibilities **This point seems a bit unfinished...?**

Months 13-24

The analysis of the three disks with high angular resolution and high sensitivity multi-wavelength ALMA observations and complementary high-contrast near infrared imaging will be completed. The data will be compared with models developed as part of other projects in the RU to understand if the different dust and gas properties and the potential detection of planetary mass companions are consistent with an evolutionary scenario. The data will constrain the model predictions for the development of gaps (in dust and gas) in the two full disks, and the hole and dust/gas properties in the TD.

Months 25-36

Depending on the results of the analysis of the three disks and the quality of the data for resolved disks in the ALMA archive, we will expand the study of disks at high angular resolution.

2.6 Data handling

ESO is acquiring a dedicated computing cluster for the processing of science data from ALMA (and other observatories/instruments). The computing cluster architecture is copied from the ALMA Regional Centre Cluster architecture, this ensures that all ALMA data processing applications can be used and will work at peak efficiency. We expect to have direct access to this system once will be installed and open to the ESO astronomers (expected by February 2017).

Our group at ESO has direct access to a high-end server that we used for the analysis of the Lupus disks presented in Tazzari et al. (2017). This server has an hybrid multi-CPU (2 CPUs with 14 compute cores, each capable of double threading), multi-GPU (2 NVIDIA Tesla-K40) architecture that we used to develop and test the advanced data analysis software developed in Tazzari (2016b).

We have access to, and we will continue to use for this project, the computing facilities in the Garching campus offered by the Excellence Cluster (the C2PAP cluster) and the Max Planck Institutes (the Hydra cluster). We have already been using these facilities to successfully and effectively model the dust properties and distribution in protoplanetary disks (Guidi et al. 2016; Tazzari et al. 2016a; Tazzari et al. 2017).

Given the large amount of data analysis for this project, we will need to upgrade the fast-io storage of the server in our group, which is required for effective ALMA data processing in CASA. To share data and analysis results with the rest of the team, we plan to use one of the commercially available cloud storage services (e.g. Dropbox, GoogleDrive, OneDrive, etc).

As part of this project, we will make available the re-processed ALMA data via a dedicated website. The data will be released in progressive instalments together with the publication of the research papers.

3. Bibliography

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4. Requested modules/funds

4.1 Basic Module

4.1.1 Funding for Staff

[Text]

Barbara: do we need to put the cost of the student here? Answer from Kees: yes. Salary group E13, either 75% or 50%. This is, by the way, something we have to decide for the entire Forschergruppe: do we do 50% or 75% contracts for PhD students?

4.1.2 Direct Project Costs

[Text]

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

- **laptop:** high-end laptop for new hire (3k€) **Kees to Leonardo: I fear that the DFG does not fund laptops.**
- **storage:** upgrade of the ESO data reduction server fast-io storage (3k€)
- **storage:** cloud storage service for collaboration data sharing (1.5k€)
- **software:** office suite, compilers (0.5k€) **Kees to Leonardo: I fear that the DFG does not fund non-project-specific licences.**

Total equipment cost: 8k€ **Update**

4.1.2.2 Travel Expenses

During the project we expect an average of 1 intercontinental and 2 european trip per year to work with the collaborators, plus 1 intercontinental and 2 european trip to present results at conferences and meetings. The expected cost is 3k€ for each intercontinental trip (note that one of the collaborators is in Hawaii and one in Santiago de Chile, implying relatively expensive airfares) and 1k€ for each european trip.

Total travel expenses: 10k€

4.1.2.3 Visiting Researchers (excluding Mercator Fellows)

[Text]

4.1.2.4 Other Costs

Given the distributed nature of the collaboration, we expect to organize one team meeting in Munich for this sub-project. We thus require funding to cover the general expenses of the organization of the meeting (2k€).

4.1.2.5 Project-related publication expenses

Given the distributed nature of the collaboration, it may be necessary to contribute to publication expenses for overseas journals (e.g. the Astrophysical Journal).
Total publication expenses: 1k€

4.1.3 Instrumentation

[Text]

4.1.3.1 Equipment exceeding EUR 10,000

[Text]

4.1.3.2 Major Instrumentation exceeding EUR 100,000

[Text]

5. Project requirements

5.1 Employment status information

[Text]

5.2 Composition of the project group

[Text]

5.3 Cooperation with other researchers

5.3.1 Planned cooperation on this project

5.3.1.1 Collaborating researchers for this project within the Research Unit

Please summarize here how this project is linked to the other RU projects.

5.3.1.2 Collaborating researchers for this project outside of the Research Unit

Please summarize here how this project is linked to international teams.

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

Please just provide a list of names. Maybe you can boldface those whom you work with closely.

5.4 Scientific equipment

[Text]

5.5 Project-relevant interests in commercial enterprises

[Text]

5.6 Additional information

[Text]