Final report for the project ”Study of the dust and gas components of young debris disks using infrared and millimeter technique” NKFIH/KH-130526

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1 Motivation and overview

Circumstellar debris disks are optically thin collections of solids ranging from planetesimal size bodies down to dust grains. All of the components are thought to be part of a collisional cascade in which larger objects are gradually ground to smaller particles through mutual destructive collisions. Observations are only sensitive to the lowest mass end of the population: thermal emission of dust is detectable at infrared (IR) and millimeter wavelengths, while the stellar light scattered by the disk is mostly observable in the optical/near-IR regime. Our Solar System currently harbors two very tenuous debris rings: the inner asteroid belt and the outer Kuiper belt. Studying similar debris disks around other stars helps to understand the past of our own Solar System as well.

While the population of planetesimals cannot be observed directly, their presence, location, and some characteristics can be deduced from observations of the second generation dust grains as tracers. Due to this close relationship, the study of debris dust evolution can give insight into the evolution of planetesimal belts as well. A substellar companion or a planet may sculpt the structure of the disk by clearing zones along its orbit. In addition, their dynamical perturbations may also create and maintain substructures like clumps, warps, and offsets in the disk. Observation of such structures thus can provide constraints on the presence and properties of otherwise undetectable planets. In young systems the dust production is not limited to planetesimal belts. The final accumulation of terrestrial planets thought to occur via giant collisions between planetary embryos that release a large amount of smaller fragments in the inner regions leading to strongly elevated mid-IR emission for a period. To the best of our knowledge, the so called extreme debris disks are the best candidates for studying this process.

Though, previously, debris disks were thought to be gas poor, recent observations of millimeter CO lines revealed copious amount of gas in some 20 systems. This offers a new way to investigate debris disks. If the observed gas is released from erosion of icy planetesimals, then the detected gas species allow us to probe the ice content and composition of the parent bodies. Some of the identified gas-bearing systems have also been suggested to be of a hybrid nature, where the gas is primordial, leftover from the protoplanetary disk phase, while the dust is second generation. The presence of long-lived residual primordial gas could have an important impact on formation of planetary atmospheres and would pose a serious challenge to current disk evolution models.

In our project we mainly focused on young debris disks, paying special attention to study their gas content and to clarify the origin of the observed gas (section 2.1). Using continuum millimeter observations we also investigated the morphology of the planetesimal belts as well as the dust size distribution in some carefully selected young sytems (sect. 2.2). In addition, we dealt with the methodology of observations of debris disks (sect. 2.3), and as the first step in a longer-term project, we discovered and studied new extreme debris disks (sect. 2.4).

The project was based primarily on the work of two researchers, Attila Moór and Péter Ábrahám. In addition, Krisztián Vida joined the group for a year, and provided a substantial contribution to our studies on the host stars of the targeted debris disks.

Our investigations led to the publication of 12 papers in high-impact astronomical journals. One additional paper is under review, for which a favourable referee report was received. We also presented our results at several international conferences/workshops with five oral talks and four posters. In addition, together with the Max Planck Institute for Astronomy (Heidelberg) we were the co-organizer of the "Current and future trends in debris disk science II" international workshop that was held in 2019 at the Konkoly Observatory (Budapest). This workshop offered an opportunity to the 38 participating experts to discuss a wide range of topics in the field of debris disks and to arrange future joint projects.

Our research generated new questions that we need further measurements to answer. During the project term we were principal investigators or co-investigators of a number of successful observing time applications at major ground-based observatories to study these issues (see section 3 for the details). The results obtained in these observational projects are the basis for future publications.

A more detailed summary of our science achievements is provided below.

2 Science results

2.1 Investigation of gas-bearing debris disks.

Recent years have seen the discovery of a growing number of debris disks with observable amounts of CO gas. Based on the observed CO masses, gas-bearing debris disks can be divided into two groups. Roughly half of the objects have a small CO mass ($< 10^{-4}\,M_\oplus$). In these systems the gas is of secondary origin, stems from the destruction of larger icy planetesimals. There are, however, a handful of disks – all found around young (<50 Myr) A-type stars – that harbor CO masses comparable to protoplanetary disks ($>0.01\,M_\oplus$). Explaining these CO-rich systems with secondary gas production is challenging, since by considering the typical photodissociation lifetime of CO molecules they would require unrealistically high CO production rates. The young age of these systems raises the possibility that they rather contain leftover gas from the protoplanetary phase, where the abundant H_2 molecules can shield CO molecules from photodissociation caused by interstellar/stellar UV photons. Alternatively, recent studies demonstrated that shielding by neutral carbon gas produced mainly from photodissociation of CO and CO_2 in tandem with self-shielding by CO molecules can prolong the photodissociation lifetime significantly, allowing large CO masses to accumulate. If we want to understand the origin of these CO-rich disks, then in addition to CO, it is also important to study their carbon gas content. In our project we primarily focused on the study of CO-rich debris disks with a special emphasis on the origin of the gas in these systems.

New Millimeter CO Observations of the Gas-rich Debris Disks 49 Cet and HD 32297.
Using the Atacama Large Millimeter/submillimeter Array (ALMA) 7-m Array we observed ^{13}CO and $C^{18}O$ emission toward two previously identified gas-bearing debris disks, 49 Cet and HD 32297. By analyzing the obtained data we found that both systems have high CO content with $M_{CO} > 0.1\,M_\oplus$, i.e. they can be classified as CO-rich debris disks. Adapting a recent secondary gas disk model that considers both shielding by carbon atoms and self-shielding of CO, we can explain the observed CO level in both systems. However, based on the available data, the primordial origin of the observed CO gas cannot be ruled out either. Based on the derived gas densities we suggest that, in the HD 32297 disk, dust and gas are coupled and the dynamics of small grains is affected by the gaseous component. For 49 Cet, the question of coupling remains undecided (**Moór et al., 2019, ApJ, 884, 108**).

Physical Conditions of Gas Components in Debris Disks of 49 Ceti and HD 21997.
To further characterize the gas component of 49 Cet and HD 21997 (the latter was the first known CO-rich disk in the literature, discovered by our group) we have conducted non-LTE (local thermodynamic equilibrium) analyses of the rotational spectral lines of CO. By assuming wide range of H_2 density, the observed CO line intensities could be reproduced as long as the H_2 density was higher than $10^3\,cm^{-3}$. Regardless whether H_2 molecules or electrons are assumed to be the primary collisional partners of CO molecules, we derived high CO column densities $2–15\times10^{17}\,cm^2$) and low gas temperatures (8–12 K) for both disks. We concluded, that CO molecules can be excited in environments containing no H_2 or a small number of H_2 molecules, even where collisions with CO, C, O, and C^+ would make an important contribution to the CO excitation in addition to H_2. Meanwhile, our result does not rule out the case of abundant H_2 molecules (**Higuchi et al., 2020, ApJ, 905, 122**).

The Surprisingly Low Carbon Mass in the Debris Disk around HD 32297.
The presence of significant amount of neutral carbon gas in CO-rich debris disks is an important prediction of the current secondary gas models, which is yet to be verified in most of these objects. Using the ALMA interferometer,

therefore we searched for carbon gas in HD 32297. Our observations revealed a ring of neutral carbon gas at ∼110 au with a characteristic width of 80 au around the star. The mass of the carbon gas is only $3.5 \pm 0.2 \times 10^{-3}$ $M_{\oplus}$, about two orders of magnitudes smaller than what our secondary gas model in Moór et al. (2019) predicted based on the CO measurements alone. To explain both carbon and CO observations we explored several possible models and we found that the most likely scenario is one where the carbon gas is rapidly removed on a timescale of order a thousand years and the system maintains a very high CO production rate of 15 $M_{\oplus}$/Myr, much higher than the rate of dust grind-down. We proposed a possible scenario to meet these peculiar conditions: the capture of carbon onto dust grains, followed by rapid CO re-formation and re-release. In steady state, CO would continuously be recycled, producing a CO-rich gas ring that – in accordance with the observations – shows no appreciable spreading over time (**Cataldi et al., 2020, ApJ, 892, 99**).

A Deep Search for Five Molecules in the 49 Ceti Debris Disk.
One possible approach to assess the origin of gas in CO-rich debris disks is to investigate their chemistry. If the gas has primordial nature then its mass is dominated by H_2 molecules, whose presence lead to a significantly different chemical environment than in an H_2-poor secondary gas disk. Detecting other molecules than CO and thus better understanding the composition of the gas in debris disks can help us to elucidate the origin of the gas and, if the gas proves to be of secondary origin, to constrain the ice abundance of exocomets. Motivated by these opportunities, we used the ALMA 12-m array to perform a deep search for five molecules (CN, HCN, HCO^+, SiO, and CH_3OH) in the debris disk around 49 Cet. Our search yields stringent upper limits on the flux of all surveyed molecular lines, which imply abundances relative to CO that are orders of magnitude lower than those observed in protoplanetary disks and Solar System comets, and also those predicted in outgassing models of second-generation material. However, if carbon shielding is responsible for extending the lifetime of any CO produced in second-generation collisions, then the line ratios do not reflect true ice phase chemical abundances, but rather imply that CO is shielded by its own photodissociation product, carbon, while other molecules are rapidly photodissociated by the stellar and interstellar radiation field (**Klusmeyer et al., 2021, accepted for publication in ApJ, arXiv:2107.07435**).

Lack of other molecules in CO-rich debris discs: is it primordial or secondary gas?
Aimed at elucidating the origin of the gas content in CO-rich debris disks we carried out millimeter molecular line observations toward four CO-rich debris disks (HD 21997, HD 121617, HD 131488, and HD 131835) and, for five protoplanetary or transitional disks around Herbig Ae stars (HD 100453, HD 139614, HD 142666, and HD 145718). The latter subsample was used as a comparison to give a picture about the characteristic line ratios in protoplanetary gas material. None of the five targeted molecules (CN, HCN, HCO^+, C_2H, and CS) were detected in the four debris disks and in the transitional disk around HD 141569, whereas they were measurable in the four protoplanetary disks. Using chemical and radiative transfer modelling, we show that the abundances of molecules other than CO in debris disks are expected to be very low. We consider multiple sets of initial elemental abundances with various degrees of H_2 depletion. We find that the HCO^+ lines should be the second brightest after the CO lines, and that their intensities strongly depend on the overall CO/H_2 ratio of the gas. However, even in the ISM-like scenario, the simulated HCO^+ emission remains weak as required by our non-detections (**Smirnov-Pinchukov, Moór, Semenov, Ábrahám et al., 2021, submitted to MNRAS, a favourable referee report was received**).

A multiwavelength study of the debris disc around 49 Cet.
The presence of gas in debris disks can influence the dynamics and the spatial distribution of dust particles. These small grains that are most affected by gas drag can be well traced in high spatial resolution scattered light images of the disks. To study the spatial distribution of dust in the disk of 49 Cet we combined a former coronagraphic H-band and our new Y-band images from the Very Large Telescope SPHERE instrument. Using the disk's radial extent from ALMA observations and the grain size distribution by spectral energy distribution fitting we generated semidynamical dust models of the disk. A disk with a maximum surface density at 110 au and shallow edges can describe both the thermal emission and the scattered light observations. This suggests that small grains close to the blow-out limit and large grains stem from the same planetesimal population and are mainly influenced by radiation pressure. We found no any observational evidence of significant gas-dust interaction. There is no sign of unusual pile-up of grains smaller than the blowout limit or the formation of a narrow ring of small particles at the edge of the gas disk (**Pawellek et al., 2019, MNRAS, 488, 3507**).

Exocomets: A spectroscopic survey.
Production of secondary gas is not limited to erosion of icy planetesimals in the outer disk, evaporation of exocomets

getting too close to the star can also be accompanied with gas liberation. Gas material released in this way have already been reported to detect via optical absorption lines at 20 stars. Aimed at expanding the sample of known exocomet-host stars we conducted a large survey in which we obtained high-resolution optical spectra of 117 main-sequence stars with spectral types ranging from B8 to G8. By analyzing Ca II H&K and Na I D lines we detected narrow non-photospheric interstellar or circumstellar (CS) absorptions towards 60 stars. For 30 objects, at least one of the detected narrow lines can be attributed to CS gas. Similarly to previous works, hot CS gas is only detected towards stars earlier than A9. We found that the probability of finding CS gas in stars with larger projected velocity (and thus likely more edge-on) is higher. We also found a weak trend with the presence of near-IR excess and with anomalous λ Boo-like abundances, but this would require confirmation by expanding the sample (**Rebollido, 2020, A&A, 639A, 11**).

2.2 Continuum millimeter observations of young debris disks.

By allowing high spatial resolution and unprecedentedly sensitive observations of cold dust, the ALMA interferometer offers a unique opportunity to study the morphology of debris disks at millimeter wavelengths. At these long wavelengths continuum images trace primarily the emission of dust grains larger than a few hundred μm. Since such large debris particles are little influenced by stellar radiative/wind forces they retain the orbital characteristics of their larger parent bodies and thus can serve as a proxy for the spatial distribution of unseen planetesimals. By supplementing ALMA data with even longer wavelength observations allows to determine the exponent of the slope of the disk emission spectrum at millimeter wavelengths that encodes information on the grain size distribution. The latter parameter can give an insight into the collision processes taking place in the disk.

The Big Sibling of AU Mic: A Cold Dust-rich Debris Disk around CP-72 2713 in the β Pic Moving Group.
Based on Spitzer and Herschel archival far-IR measurements we identified a debris disk around the young (~24 Myr old) K7/M0 star CP-72 2713. By obtaining 1.3 mm continuum images with the ALMA 7-m array we revealed a very extended disk peaking at a radius of ~140 au. The dynamical excitation of the belt at this radius is found to be reconcilable with planetary stirring, while self-stirring by large planetesimals embedded in the belt can work only if these bodies form very rapidly, e.g. via pebble concentration. By analyzing the obtained SED we found that the excess spectrum is almost identical to a pure blackbody with a temperature of 43 K and a fractional luminosity of 1.1×10^{-3}. The latter value is prominently high, we know of only four other similarly dust-rich Kuiper-belt analogs within 40 pc of the Sun. Currently, very few disks around later spectral-type stars are known, and so far only a couple of them have been spatially resolved. Therefore, thanks to its brightness, proximity, and favorable orientation the disk of CP-72 2713 may play an important role in the future in understanding the physics of debris disks around late spectral-type stars (**Moór et al., 2020, AJ, 159, 288**).

Resolving Structure in the Debris Disk around HD 206893 with ALMA.
HD 206893 is one of those two known systems where a brown dwarf orbits interior to a debris disk. This configuration provides a rare and valuable opportunity to study the possible interactions between the companion and the disk material and to place dynamical constraints on the mass of a directly imaged companion. Our ALMA observations at 1.3 mm revealed a broad distribution of planetesimals extending from radii <51 au to 194^{13}_{-2} au with a statistically significant evidence for a gap in the dust disk with inner radius 63^{+8}_{-16} au and width of 31^{11}_{-7} au. Since the inner radius of the disk is not resolved by the measurements we can place only a modest upper limit on the mass of the brown dwarf companion of <1170 $M_{\rm Jup}$. The origin of the serendipitiously discovered gapped structure is still unclear: it could be inherited from the protoplanetary disk phase or carved by one or more additional, unseen companions at larger separation in the system. If the gap is carved by a single planet on a circular orbit, chaotic zone theory predicts that it should have a mass of 1.4 $M_{\rm Jup}$ at a semimajor axis of 79 au. Interestingly, among the six systems that have so far been surveyed at sufficient resolution and sensitivity with ALMA, four showed similar gapped structure (**Nederlander et al., 2021, ApJ, 917, 5**).

Four new PLanetesimals Around TYpical and Pre-main seqUence Stars (PLATYPUS) Debris Discs at 8.8 mm.
Using the Australian Telescope Compact Array (ATCA) we have performed 8.8 mm dust continuum observations for debris disks around four young stars (HD 48370, CP-72 2713, HD 131488, and HD 32297). We detected all four targets and derive a grain size power law index (q) that is consistent with collisional cascade models and theoretical predictions for parent planetesimal bodies where binding is dominated by self-gravity. By combining our sample

with other millimetre-wavelength detected debris discs from the literature we obtain a weighted mean of q values (<q>=3.31) which is close to analytical predictions for a classical steady state collisional cascade model. We suggest possibility of two distributions of q; a broad distribution (where q ranges between 3.2 and 3.7) for "typical" gas-poor debris disks and a lower distribution (where q<3.2) for bright gas-rich debris disks. Alternatively, an observational bias may be present between the grain size distribution parameter and absolute flux which is likely attributed to the detection rates of faint debris disks at cm wavelengths (**Norfolk et al., 2021, MNRAS, 507, 3139**).

2.3 Methodology of debris disk observations

Dust spreading in debris discs: do small grains cling on to their birth environment?
We examined the possibility of locating parent planetesimal belts of debris discs by observing their dust emission at different wavelengths. The traditional way is using resolved images at millimetre wavelengths which probe large dust grains that are co-located with their parent bodies. Smaller particles seen in the IR are subject to several non-gravitational forces that move them away from their birthplace and so may not closely trace the planetesimals. We concluded that tracing the planetesimal belts of debris discs around early- and solar-type stars is possible even at mid-IR wavelengths. For disks around M-type stars, however, millimeter observations are indispensable because the dust best visible in the IR is efficiently displaced inwards from their birth location by stellar winds, causing the disk to look more compact in IR images than the planetesimal belt (**Pawellek et al., 2019, MNRAS, 487, 5874**).

The MESAS Project: Long-wavelength Follow-up Observations of Sirius A.
Accurate models of millimeter emission of stars are essential not only to understand fundamental stellar processes, but also to assess the presence of dusty debris in spatially unresolved observations of circumstellar disks. However, long wavelength spectra of main-sequence stars remain a largely uncharacterized aspect of stellar astronomy due to the lack of observational data in this regime. To improve this situation we obtained new radio observations of Sirius A, the closest main-sequence A-type star, at 1.4–9.0 mm. We found that our measurements are in good agreement with previous observations and PHOENIX model of the Sirius A's stellar atmosphere. Our data can be used as a long-wavelength template of stellar emission for A-type stars (**White et al., 2019, ApJ, 875, 55**).

2.4 Study of extreme debris disks

Extreme debris disks (EDDs) constitute a special, peculiarly dust-rich subclass of warm debris disks. Contrary to typical debris disks the observed very high dust content of EDDs cannot be explained by the steady state collisional grinding of an in situ planetesimal belt that started its evolution when the system was formed but instead point to a recent large dust production event – likely related a giant collision – occuring in the inner 1–2 au. That is why, current theories suggest that these disks are associated with the formation of terrestrial planets, that are expected to be hallmarked by numerous collisions among planetary embryos present in the inner regions after the dispersal of the protoplanetary disk.

A New Sample of Warm Extreme Debris Disks from the ALLWISE Catalog.
Using a combined data set, based on the AllWISE mid-IR photometric and the Tycho-Gaia astrometric catalogs we identified 6 new EDDs, all surround Sun-like (F5-K7) main-sequence stars located within 300 pc. We concluded that four of these disks exhibited variable mid-IR emission between 2010 and 2019. By analyzing the sample of all known EDDs, now expanded to 17 objects, we found that 14 of them showed changes at around 4μm over the past decade, suggesting that mid-IR variability is an inherent characteristic of EDDs. These rapid changes in the thermal emission of the disks also point to a recent violent collision event. We also reported that wide-orbit pairs are significantly more common in EDD systems than in the normal stellar population. While current models of rocky planet formation predict that the majority of giant collisions occur in the first 100 Myr, we found that the sample of EDDs is dominated by systems older than this age. This raises the possibility that the era of giant impacts may be longer than we think, or that some other mechanism(s) can also produce EDDs. We examined a scenario where the observed warm dust stems from the disruption and/or collisions of comets delivered from an outer reservoir into the inner regions, and explore what role the wide companions could play in this process (**Moór et al., 2021, ApJ, 910, 27**).

Discovery of additional warm extreme debris disks.
Our search for new extreme debris disks has not been finished with the previous work. Using the much deeper and more accurate Gaia EDR3 catalog instead of Tycho-Gaia, along with the AllWISE catalog we have discovered and examined 15 additional EDD candidates. Our results about these disks were presented at the European Astronomical Society Annual Meeting (EAS2021):
1) *"A new sample of warm extreme debris disks", A. Moór (talk)*;
2) *"Extreme time variability of extreme debris disks", P. Ábrahám (talk)*
(`https://eas.kuoni-congress.info/2021/programme/`).

3 Accepted observing proposals during the time period of our project

- Projects on the Atacama Large Millimeter/submillimeter Array
  1. *Gas around MS stars: A common exocometary origin for hot and cold gas*, PID: 2019.1.01517.S (Cycle 7), PI: Isabel Rebollido, Co-I: Attila Moór
  2. *The first minisurvey for neutral carbon gas in debris disks around G-type stars to test secondary gas disk models*, PID: 2019.1.01603.S/2019.2.00208.S (Cycle 7), PI: Attila Moór, Co-I: Péter Ábrahám
  3. *What are the best conditions for shielded debris disks?*, PID: 2021.1.01487.S (Cycle 8), PI: Attila Moór, Co-I: Péter Ábrahám
  4. *Are CO-rich debris disks primordial or secondary?*, PID: 2021.1.00621.S (Cycle 8), PI: Gianni Cataldi, Co-I: Attila Moór
  5. *The C content of debris disks around young A-stars*, PID: 2021.1.00629.S (Cycle 8), PI: Gianni Cataldi, Co-I: Attila Moór

- Projects on the Very Large Telescope
  1. *First spatially resolved observations of an extreme debris disc following a dust-releasing impact event*, PID: 103.2038, instrument: MATISSE, PI: Lei Chen, Co-I: Attila Moór, Péter Ábrahám
  2. *Multi-epoch spatially resolved observations of an extreme debris disc following a dust-releasing impact event*, PID: 105.20ER, instrument: MATISSE, PI: Lei Chen, Co-I: Attila Moór, Péter Ábrahám
  3. *Insight into the formation of rocky planets: observation of a new sample of extreme debris disks with VISIR*, PID: 106.212F, instrument: VISIR, PI: Attila Moór , Co-I: Péter Ábrahám
  4. *The mysterious origin of extreme debris disks revealed by mid-infrared interferometry*, PID: 108.229P, instrument: MATISSE, PI: József Varga, Co-I: Attila Moór, Péter Ábrahám