Laboratory Astrophysics: from Observations to Interpretation
Proceedings IAU Symposium No. 350, 2019
F. Salama & H. Linnartz, eds.
doi:10.1017/S1743921319007154

Dust in debris disk: Observations and laboratory experiments

Johan Olofsson[1,2]

[1]Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Av. Gran Bretaña 1111, Playa Ancha, Valparaíso, Chile
email: johan.olofsson@uv.cl

[2]Núcleo Milenio Formación Planetaria - NPF, Universidad de Valparaíso, Av. Gran Bretaña 1111, Valparaíso, Chile

Abstract. Debris disks are the natural by-products of the star and planet formation processes. Since the 1980's several thousands of debris disks have been detected, and the presence of a disk is inferred by the detection of excess emission over the photospheric emission. This thermal emission arises from (micron-sized or slightly bigger) dust grains heated by the central star. However, in the vast majority of cases, these observations are not spatially resolving the radial distribution of the dust, resulting in strong degeneracies in the modeling approach (radial distance vs minimum grain size mostly). Therefore the properties of the small dust grains remained largely unconstrained until the arrival of high angular resolution instruments, especially at optical and near-infrared wavelengths. In these proceeding some of the main results are presented that have been obtained over the past few years on the properties of small dust grains in debris disks, and it is discussed how laboratory experiments contributed to put those results in context.

Keywords. stars: circumstellar matter, techniques: high angular resolution

1. Introduction

Shortly after the collapse of the primordial molecular cloud, a gas-rich disk forms around the central proto-star. The mass of the disk is dominated by the gas,but the disk also contains small dust grains (thought to be about 1% of the total mass). The sub-micron sized grains should start growing efficiently and rapidly in the disks, and start to form pebbles, boulders, and planetary embryos. After a few Myr the gas starts to dissipate (e.g., via photo-evaporation), and only planetesimals and already formed planets remain (see Wyatt 2008; Matthews *et al.* 2014; Hughes, Duchêne & Matthews 2018 for reviews on debris disks). The process of planetary formation is a challenging one, with several obstacles along the way, such as the radial drift barrier that should efficiently remove grains that are large enough (a few millimeters) to decouple from the gas in the disk. Nonetheless, given the recent statistics about planet detection, it is clear that planet formation is an efficient process (e.g., Dressing & Charbonneau 2015 for low-mass stars).

Nonetheless, for debris disks, more massive analogs of the asteroid and Kuiper Belts of the solar system, the problem is reversed; the lifetime of the small dust grains is much shorter than the age of the central star, due to radiation pressure, stellar winds, or Poynting-Robertson drag. Given the fact that observations are sensitive to grains smaller than 100 μm−1 mm, this means that the population of small dust grains has to be replenished somehow. It is thought that they are continuously produced in a collisional cascade, in which planetesimals collide with each others, producing smaller and smaller boulders, and in the end being ground down to a few microns. However this process is largely unconstrained from an observational point of view, mostly because we cannot detect the vast majority of the size distribution.

Debris disks are most commonly studied via the spectral energy distribution (SED hereafter), in which we detect the thermal emission of the small dust grains over the photospheric emission. Space missions such as *Spitzer* or *Herschel* have helped tremendously in our understanding of debris disks in the solar neighborhood (e.g. Eiroa *et al.* 2013). But such observations are spatially unresolved (or only marginally resolved), meaning that the radial distribution of the dust grains is largely unconstrained. This leads to very degenerate results when trying to model the SED of disks, especially between the minimum grain size and the distance of the disk to the star. As a consequence very little information can be obtained on the properties of the grains responsible for the thermal emission.

Over the past years, significant progress has been made on the topic of debris disks thanks to high angular resolution observations, especially at optical and near-infrared wavelengths, with instruments such as GPI (Perrin *et al.* 2015), SCExAO (Currie *et al.* 2017), or SPHERE (Beuzit *et al.* 2019), among others. By better constraining the radial distribution of the dust grains in the disk, these observations help alleviate the number of free parameters in the modeling, and hence provide new and valuable constraints on the grain size distribution in debris disks. But most importantly, *spatially resolved* observations in scattered and polarized light opened a new avenue to study the dust properties in debris disks, by measuring their phase function.

The phase function is the measure of the surface brightness as a function of the scattering angle† (the angle between the star, the dust grain that is scattering light, and the observer). It can be extremely useful to asses the typical sizes as well as the structures of the grains that are scattering the stellar light. Several studies have been led in the 2000s, aiming at constraining the phase function of a handful of debris disks, and they were mostly based on space-based facilities such as the *Hubble Space Telescope* (e.g., Augereau & Beust 2006). But in the past years, the number of debris disks detected at high angular resolution increased significantly, thanks to new data processing techniques such as angular differential imaging (Marois *et al.* 2006, applied in Buenzli *et al.* 2010; Thalmann *et al.* 2011, 2013; Boccaletti *et al.* 2012; Lagrange *et al.* 2012), re-processing of archival data (e.g., Soummer *et al.* 2014; Choquet *et al.* 2016), or the new generation of instruments (Currie *et al.* 2015; Kalas *et al.* 2015; Kasper *et al.* 2015; Esposito *et al.* 2016; Lagrange *et al.* 2016; Millar-Blanchaer *et al.* 2016; Olofsson *et al.* 2016; Wahhaj *et al.* 2016; Engler *et al.* 2017; Feldt *et al.* 2017; Matthews *et al.* 2017; Milli *et al.* 2017; Esposito *et al.* 2018; Olofsson *et al.* 2018; Sissa *et al.* 2018; Engler *et al.* 2019; Gibbs *et al.* 2019; Milli *et al.* 2019, among others). All these studies have revealed a diversity of morphologies for the disks, with different ranges of inclinations, different radii, radial extent, some disks displaying several belts, and possibly some spirals arms.

There are however two caveats, or rather, trade-offs, when studying debris disks. First, they are relatively faint, and not all observations can yield meaningful determinations of the phase function, but the great advantage of debris disks is that they are optically thin, and therefore the assumption of single scattering events can be made, meaning that we are really able to characterize the dust properties in a direct, model-independent, way. The second caveat is with respect to the inclination; one can only probe scattering angles in the ranges $[90 - i, 90 + i]$ degrees, where i is the inclination ($0°$ being face-on, and i being always smaller or equal to $90°$). Therefore for face-on disks, the range of scattering angles is rather narrow, limiting the determination of the full phase function, but the disk is well detected. On the other hand, for highly inclined disks, the semi-minor axis is

† In the following, small scattering angles denote forward scattering, while large scattering angles denote backward scattering

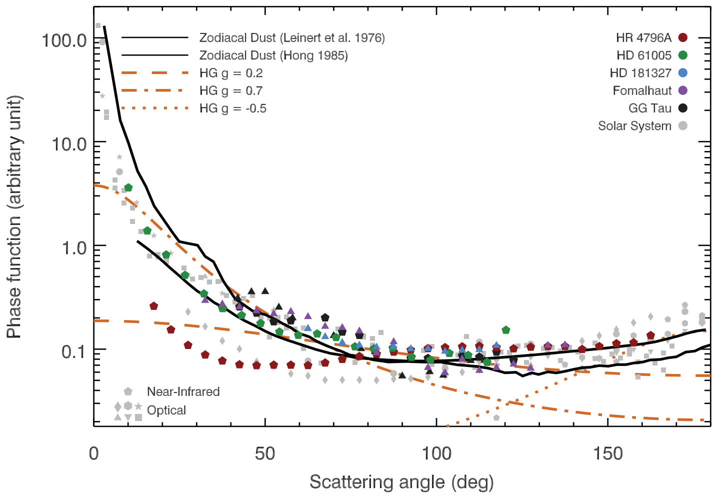

Figure 1. Scattered light phase function of three debris disks (HR 4796, HD 61005, and HD 181327), figure taken from Hughes, Duchêne & Matthews (2018).

compressed due to projection effects, and therefore the disk is not well detected for all the azimuthal angles (with the risk of not having any azimuthal information if $i = 90°$, see the case of AU Mic for instance, e.g., Augereau & Beust 2006). But on the other hand, the range of scattering angles probed is much larger, yielding to a much better determination of the phase function. There seems to be a "sweet spot" for inclinations between $70 - 80°$. In the following, we will summarize the recent findings on the topic of the phase function from scattered and polarized light emission, the current limitations, as well as the current interpretation based on laboratory experiments.

2. Scattered and polarized phase function

Figure 1, taken from Hughes, Duchêne & Matthews (2018), shows the most recent compilation of the scattered light phase function for three debris disks, HR 4796 (Milli *et al.* 2017), HD 61005 (Olofsson *et al.* 2016), and HD 181327 (Stark *et al.* (2014)). All three phase functions seem to display a relatively similar behavior, with a relatively flat dependency to the scattering angle at around 90° and an increase at short scattering angles, indicative of strong forward scattering. It is to be noted that the phase function of HR 4796 as reported in Milli *et al.* 2017 is probed at even smaller scattering angles and the forward scattering peak is more pronounced. Only for HR 4796 there is enough signal of the back side of the disk (the side away from earth) so that the phase function can be measured, and it shows a hint of backward scattering. If one were to model those phase functions using the Mie theory, therefore assuming compact spherical dust grains, one would find that the dust grains in debris have to be larger than the wavelength of observations.

Nonetheless, there is another diagnostic that can be used to better constrain the dust properties, which is the polarized phase function†. Several contemporary direct imaging

† There is a small abuse of language here; light becomes polarized because it is scattered off a dust grain. Therefore polarized light is scattered light. But in the following, we will refer to scattered light as the Stokes vector I and to the polarized light as the azimuthal polarized intensity Q_ϕ, which is constructed from the Stokes vectors Q and U.

https://doi.org/10.1017/S1743921319007154 Published online by Cambridge University Press

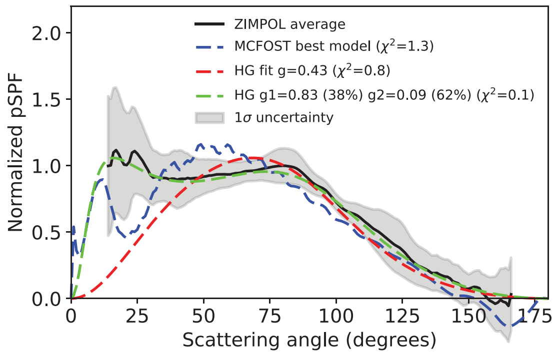

Figure 2. Polarized intensity as a function of the scattering angle for HR 4796 at optical wavelengths using SPHERE/ZIMPOL (taken from Milli *et al.* 2019).

instruments are able to measure the Q and U Stokes vectors, and it is possible to derive the azimuthal polarization of light scattered by the small dust grains (see e.g. Benisty *et al.* 2015; Perrin *et al.* 2015). We can then measure the *polarized intensity* as a function of the scattering angle. One should note that nowadays we barely have access to the *polarization fraction* (the polarized intensity divided by the total intensity), due to the challenge of accurately measure the true total intensity (see Milli *et al.* 2012 for instance), but it has been measured for a handful of debris disks (Perrin *et al.* 2015; Engler *et al.* 2019 but in the latter only the radial dependency could be measured and not the azimuthal dependency). Figure 2 shows an example of the polarized intensity as a function of the scattering angle for HR 4796 (taken from Milli *et al.* 2019). The polarized phase function shows a peak at around 80° while flattening at smaller scattering angle. If one divides this phase function by the scattered light phase function, the *polarization fraction* would resemble a Bell curve peaking at around 90° (keeping in mind that the polarized phase function in Fig. 2 is measured at optical wavelengths, while the scattered light phase function of Fig. 1 is measured at near-infrared wavelengths). If we once again use the Mie theory (making the strong hypothesis that dust grains are compact spheres), we would find that the dust grains must be smaller than the observing wavelengths. There is therefore a strong disagreement in the interpretation of the polarized and scattered light phase function, which can be traced back to the hypothesis that grains are compact spheres. Similar conclusions were reached in Olofsson *et al.* (2016) for instance.

One should note that our interpretation of optical or near-infrared observations of the phase function is currently limited by the fact that we can hardly measure the polarization degree as a function of the scattering angle. But there are currently ongoing efforts to tackle this challenge, which lies in determining the total intensity surface brightness of the disks, for instance by performing "reference differential imaging". This approach consists of finding the most similar point spread function to the one obtained during the observations of the target of interest, from a gigantic library of point spread functions, and subtract it to the observations. This technique would avoid subtracting astrophysical signal coming from the disk, as it can be the case when using (most) "angular differential imaging" algorithms, and would also allow to detect disks that are not highly inclined (see Milli *et al.* 2012 for more detail on the drawbacks of using angular differential imaging). This data reduction process usually works best for space-based observations due to the increased stability of the instrument, and is quite challenging for ground-based instruments due to the variations of the atmosphere and observing conditions, but preliminary results are very encouraging.

https://doi.org/10.1017/S1743921319007154 Published online by Cambridge University Press

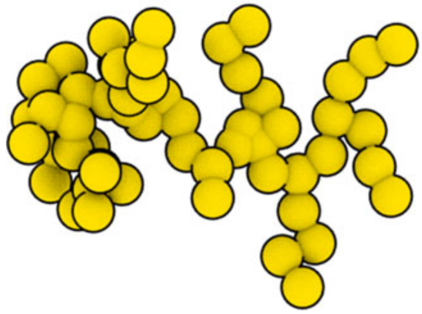

Figure 3. Sketch of an agglomerate, composed of smaller monomers.

3. Reconciling scattered and polarized light observations

As mentioned before, there is an apparent contradiction in the interpretation of the phase functions obtained in scattered light and polarized light. This contradiction lies in the use of the Mie theory, which assumes spherical compact grains. The Mie theory, which has been widely used because it is computationally fast, already demonstrated some shortcomings when modeling scattered light images (e.g., Lebreton *et al.* 2012), but there is now even more reason to explore alternative solutions to best exploit the high-end observations delivered by the new generation of high contrast imaging instruments.

One possible alternative to account for the observations is to consider that the dust grains in debris disks are agglomerates of small monomers (see Figure 2 for a sketch of such an agglomerate). The optical properties of such dust "grains" have been studied for instance in Min *et al.* 2016; Roy *et al.* 2017; Halder *et al.* 2018; and Tazaki *et al.* 2019. Those studies have demonstrated that both the scattered light phase function and the polarized phase function can reproduce the observations; with strong forward scattering in total intensity (as well as some backward scattering) and a polarization degree peaking at around 90°, for a variety of agglomerate sizes. One of the conclusion of Min *et al.* 2016 is that what dominates the behavior of the scattering phase function is the overall size of the aggregate (hence large compared to the wavelength), while the polarized phase function is mostly dominated by the size of the individual monomers (smaller than the wavelength of observation). One of the main challenge of computing the optical properties of aggregates (e.g. using the "Discrete Dipole Approximation", Purcell & Pennypacker 1973; Draine & Flatau 1994), is that the computation time is extremely large. A possible way to circumvent the issue is to use a combination of effective medium theory, porosity, and computing the optical properties using the "Distribution of Hollow Spheres" (Min *et al.* 2016, 2005). To the best of our knowledge, such a systematic study has not yet been performed for observations of debris disks.

4. Comparison with solar system objects

Given the relatively close resemblance between debris disks and the asteroid and Kuiper Belts of the solar system, it is definitely of interest to try and compare observations of debris disks to measurements done for various solar system bodies. For instance, Frattin *et al.* 2019 measured the scattering phase function and polarization degree as a function of the scattering angle for seven samples of cometary dust analogues (one has to note that the convention of the scattering angle is reversed compared to the one adopted here). Overall, the results appear quite similar to what is measured for dust in debris disks; the scattering phase function displays a strong forward scattering peak, while also showing a significant backward scattering peak. For the degree of polarization, the peak seems

https://doi.org/10.1017/S1743921319007154 Published online by Cambridge University Press

to be slightly shifted to larger scattering angles ($\sim 80°$ in Frattin *et al.* 2019, which would translate to $\sim 100°$). Interestingly, the polarization degree shows an inversion for backward scattering, which has not yet been probed for debris disks. Concerning 67P/Churyumov-Gerasimenko, Bertini *et al.* 2019 showed that the backward scattering in the scattered light phase function is actually very pronounced, more so than what is observed in debris disks. A possible interpretation is that the grains in the vicinity of the comet are most likely larger chunks that have been ejected earlier on and are be re-captured by the comet. Overall, it seems that the dust grains in debris disks share quite some similarities with bodies of the solar system, but further investigation is required (deeper observations of debris disks, a better estimate of the polarization fraction, among other things).

5. Conclusions

Contemporary studies suggest that the dust grains in debris disks are most likely porous aggregates. The sizes of the aggregates are of the order of several microns, while the typical size of the monomers they are composed of are sub-micronic ($\sim 0.1\,\mu$m). That being said, debris disks are collision dominated environment, and the small-end of the grain size distribution is thought to be the result of the fragmentation of larger bodies. This raises the question of how the dust grains can retain their porosity, and not be compacted during collisions and subsequent fragmentation.

Studies of debris disks benefited greatly from laboratory experiments, from optical constant determination, numerical computations of optical properties, and comparison with solar system objects (in-situ or from collected samples). In the near future, to further our understanding of dust in debris disks, we will need deeper observations (to be able to detect the back side of the disks that remains mostly hidden from us in most cases), and need to improve data processing techniques so that the polarization degree as a function of the scattering angle can be accurately measured. As mentioned in Tazaki *et al.* 2019, having access to the polarization fraction *and* the color of the scattered light (observations at different wavelengths) would yield much better constraints on the porosity of the dust grains. Finally, on the topic of laboratory experiments, innovative approaches are being developed, such as the experiment led by François Ménard at the "Institut de Planétologie et d'Astrophysique de Grenoble" (France). Measuring the optical properties of any particles is a scalable problem that only depends on the size of the particle divided by the wavelength of observations. Therefore, one can build (e.g., 3D-print in that case) particles of $20-30$ cm and characterize their scattering properties by increasing the wavelength accordingly.

References

Augereau, J.-C. & Beust, H. 2006, *A&A*, 455, 987
Benisty, M., Juhasz, A., Boccaletti, A., *et al.* 2015, *A&A*, 578, L6
Bertini, I., La Forgia, F., Fulle, M., *et al.* 2019, *MNRAS*, 482, 2924
Beuzit, J., Vigan, A., Mouillet, D., *et al.* 2019, *A&A*, 631, A155
Boccaletti, A., Augereau, J.-C., Lagrange, A.-M., *et al.* 2012, *A&A*, 544, A85
Buenzli, E., Thalmann, C., Vigan, A., *et al.* 2010, *A&A*, 524, L1
Choquet, É., Perrin, M. D., Chen, C. H., *et al.* 2016, *ApJ*, 817, L2
Currie, T., Guyon, O., Tamura, M., *et al.* 2017, *ApJ*, 836, L15
Currie, T., Lisse, C. M., Kuchner, M., *et al.* 2015, *ApJ*, 807, L7
Draine, B. T. & Flatau, P. J. 1994, *J. Opt. Soc. Am. A.*, 11, 1491
Dressing, C. D. & Charbonneau, D. 2015, *ApJ*, 807, 45
Eiroa, C., Marshall, J. P., Mora, A., *et al.* 2013, *A&A*, 555, A11
Engler, N., Boccaletti, A., Schmid, H. M., *et al.* 2019, *A&A*, 622, A192

https://doi.org/10.1017/S1743921319007154 Published online by Cambridge University Press

Engler, N., Schmid, H. M., Thalmann, C., *et al.* 2017, *A&A*, 607, A90
Esposito, T. M., Duchêne, G., Kalas, P., *et al.* 2018, *AJ*, 156, 47
Esposito, T. M., Fitzgerald, M. P., Graham, J. R., *et al.* 2016, *AJ*, 152, 85
Feldt, M., Olofsson, J., Boccaletti, A., *et al.* 2017, *A&A*, 601, A7
Frattin, E., Muñoz, O., Moreno, F., *et al.* 2019, *MNRAS*, 484, 2198
Gibbs, A., Wagner, K., Apai, D., *et al.* 2019, *AJ*, 157, 39
Halder, P., Deb Roy, P., & Das, H. S. 2018, *Icarus*, 312, 45
Hughes, A. M., Duchêne, G., & Matthews, B. C. 2018, *ARA&A*, 56, 541
Kalas, P. G., Rajan, A., Wang, J. J., *et al.* 2015, *ApJ*, 814, 32
Kasper, M., Apai, D., Wagner, K., & Robberto, M. 2015, *ApJ*, 812, L33
Lagrange, A.-M., Langlois, M., Gratton, R., *et al.* 2016, *A&A*, 586, L8
Lagrange, A.-M., Milli, J., Boccaletti, A., *et al.* 2012, *A&A*, 546, A38
Lebreton, J., Augereau, J.-C., Thi, W.-F., *et al.* 2012, *A&A*, 539, A17
Marois, C., Lafrenière, D., Doyon, R., Macintosh, B., & Nadeau, D. 2006, *ApJ*, 641, 556
Matthews, B., Krivov, A., Wyatt, M., Bryden, G., & Eiroa, C. 2014, ArXiv e-prints
Matthews, E., Hinkley, S., Vigan, A., *et al.* 2017, *ApJ*, 843, L12
Millar-Blanchaer, M. A., Wang, J. J., Kalas, P., *et al.* 2016, *ApJ*, 152, 128
Milli, J., Engler, N., Schmid, H., *et al.* 2019, ArXiv e-prints
Milli, J., Mouillet, D., Lagrange, A.-M., *et al.* 2012, *A&A*, 545, A111
Milli, J., Vigan, A., Mouillet, D., *et al.* 2017, *A&A*, 599, A108
Min, M., Hovenier, J. W., & de Koter, A. 2005, *A&A*, 432, 909
Min, M., Rab, C., Woitke, P., Dominik, C., & Ménard, F. 2016, *A&A*, 585, A13
Olofsson, J., Samland, M., Avenhaus, H., *et al.* 2016, *A&A*, 591, A108
Olofsson, J., van Holstein, R. G., Boccaletti, A., *et al.* 2018, *A&A*, 617, A109
Perrin, M. D., Duchene, G., Millar-Blanchaer, M., *et al.* 2015, *ApJ*, 799, 182
Purcell, E. M. & Pennypacker, C. R. 1973, *ApJ*, 186, 705
Roy, P. D., Halder, P., & Das, H. S. 2017, arXiv e-prints, arXiv:1709.09319
Sissa, E., Olofsson, J., Vigan, A., *et al.* 2018, *A&A*, 613, L6
Soummer, R., Perrin, M. D., Pueyo, L., *et al.* 2014, *ApJ*, 786, L23
Stark, C. C., Schneider, G., Weinberger, A. J., *et al.* 2014, *ApJ*, 789, 58
Tazaki, R., Tanaka, H., Muto, T., Kataoka, A., & Okuzumi, S. 2019, *MNRAS*, 485, 4951
Thalmann, C., Janson, M., Buenzli, E., *et al.* 2013, *ApJ*, 763, L29
Thalmann, C., Janson, M., Buenzli, E., *et al.* 2011, *ApJ*, 743, L6
Wahhaj, Z., Milli, J., Kennedy, G., *et al.* 2016, *A&A*, 596, L4
Wyatt, M. C. 2008, *ARA&A*, 46, 339

https://doi.org/10.1017/S1743921319007154 Published online by Cambridge University Press