3 Prospects for the characterisation of exo-zodiacal dust with VLTI

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Exo-zodiacal dust, exozodi for short, is warm (~300K) or hot (up to ~2000K) dust found in the inner regions of planetary systems around main sequence stars. It may be located in or near the habitable zone or closer in, down to the dust sublimation distance. This is in analogy to our own zodiacal dust which is distributed between a few AU from the Sun down to ~4 Solar radii (where it forms the F-corona) with a shallow surface density profile (Kimura & Mann 1998; Hahn et al. 2002). The dust can be the most luminous component of extrasolar planetary systems, but predominantly emits in the near- to mid-infrared (IR) where it is outshone by the host star. The presence of large amounts of dust in or near the habitable zone of planetary systems is expected to be a significant obstacle for future space missions aiming to detect and characterise Earth-like exoplanets (exo-Earths, Defrère et al. 2010, Roberge et al. 2012, Stark et al. 2014). Even hot dust closer to the star may significantly degrade the coronagraphic performance at the level needed for exo-Earth imaging. It represents emission that is more extended than the star and consequently cannot be perfectly suppressed by a coronagraph. Thus, the characterisation of warm and hot exozodis is critical for the success of such missions. Furthermore, the study of the properties, distribution, and evolution of exozodiacal dust can inform about the properties and evolution of the innermost regions of planetary systems, close to their habitable zones. Interferometry provides a unique method of separating this dusty emission from the stellar emission and thus is currently the only method able to detect the dust in most of these systems. The broad wavelength coverage of the second-generation suite of VLTI instruments (and PIONIER) is particularly well suited for the characterization of exozodiacal dust systems.

3.1 Current state of the art

The presence of warm/hot dust in other planetary systems in analogy to the zodiacal dust in our own solar system has long been hypothesised. However, its detection remained elusive due to the faintness of the emission and small angular separation from even nearby stars, until near-IR interferometry using the FLUOR beam combiner at the CHARA array revealed a hot excess of ~1% in K band around the prototype debris disc host star Vega (Absil et al. 2006). Survey observations using the same method on CHARA/FLUOR and the PIONIER visitor instrument on the VLTI later revealed a larger number of these systems (Absil et al. 2013, Ertel et al. 2014). At the same time, first excesses from warm dust near the habitable zone of other stars were detected using mid-IR nulling interferometry on the Keck Interferometric Nuller (Millan-Gabet et al. 2011, Mennesson et al. 2015).

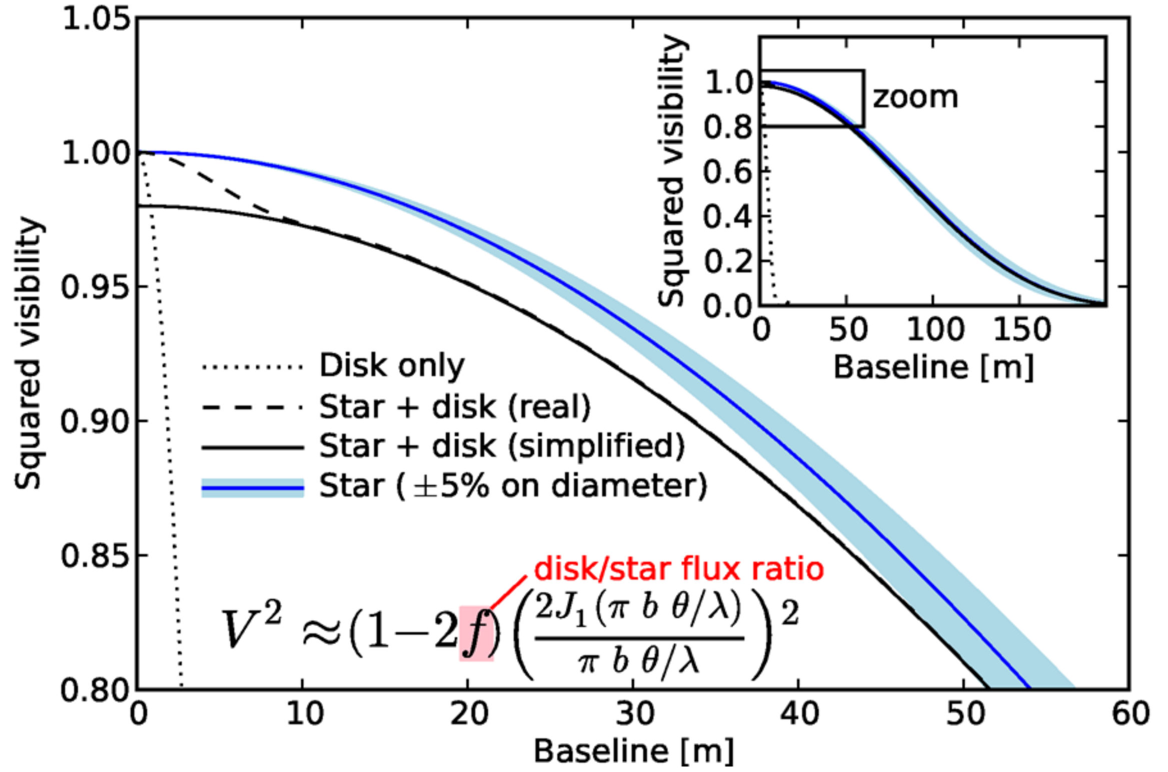

Figure 3-1: Detection strategy of hot exozodiacal dust using near-infrared optical interferometry.

3.2 Detection using optical long baseline interferometry

By far the largest number of exozodis has been detected using near-IR optical interferometry as it is used on the VLTI. Using this technique at short baselines (few 10m), the star remains mostly unresolved, resulting in fully coherent emission. In contrast, the extended emission from a dust disc is ideally fully resolved, resulting in incoherent emission and thus a visibility deficit compared to the values expected from the star alone. This visibility deficit allows for detecting the dust and the star-to-disc flux ratio can be measured as half the visibility deficit (Figure 3-1).

Due to the small flux ratio of typically 1%, only few instruments reach the accuracy on the visibility measurements necessary to detect the dust. CHARA/FLUOR and VLTI/PIONIER have been used to survey a large sample of stars for hot exozodis (FLUOR: Absil et al. 2013, K band, 42 stars; PIONIER: Ertel et al. 2014, H band, 92 stars). These surveys resulted in the first statistical constraints on the properties of hot exozodis, critical for their understanding. PIONIER in combination with the VLTI architecture was proven to be particularly well suited due to the high efficiency (simultaneous use of four telescopes) and the availability of closure phase measurements which allow one to directly distinguish between a faint companion and an extended dust disc as the cause for the detected excess (Marion et al. 2014).

3.3 New opportunities with LBT and VLT interferometry

Recently, the Large Binocular Telescope Interferometer (LBTI) started operations and will survey approx. 50 stars in the mid-IR for warm exozodis with unprecedented sensitivity. However, this survey is designed to only detect exozodis and to measure their flux levels, while only limited information on the detected systems will be derived (Defrère et al. 2016). Only the characterisation of exozodis can answer the two most urgent key questions beyond the frequency and abundance of massive dust systems:

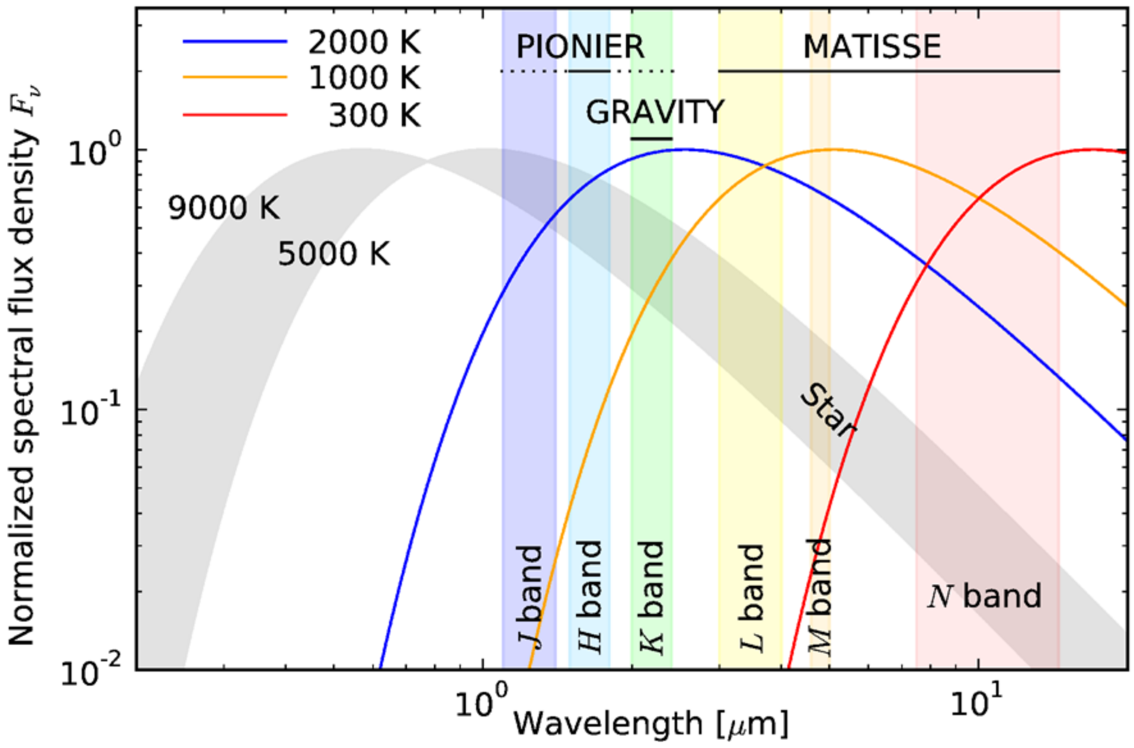

Figure 3-2: Wavelength coverage of the second-generation VLTI instruments (and PIONIER) compared to the wavelength range in which blackbody dust emission from hot and warm exozodiacal dust peaks. For PIONIER, the dotted range indicates the K band which is no longer available and the J band which may be reached with a potential instrument upgrade. Towards the shortest bands (H band and in particular J band) scattering may have a significant contribution to the total emission. The characterisation of scattered light is particularly critical for the understanding of the impact of the dust on exo-Earth imaging missions.

1. What is the connection between the warm and hot dust? This is important because most systems so far have been detected in the near-IR, but the implications of this for the presence of habitable zone dust are unclear. A tentative anti-correlation between the presence of hot and warm dust has been suggested (Mennesson et al. 2015).
2. What are the dust properties? The dust is detected as thermal emission in the mid-IR and as a potential combination of thermal emission and scattered light measured in the near-IR. Only with a detailed knowledge of the dust properties is it possible to estimate from these observations the amount of scattered light expected in the optical where future exo-Earth imaging missions will operate.

The second-generation VLTI instruments GRAVITY and MATISSE, together with PIONIER, can provide the ideal tools to address these questions through multi-wavelength measurements of the spectral energy distribution (SED) of the excess emission in near-IR to mid-IR wavelength range (Figure 3-2). In this range the emission of warm and hot dust peaks and carries most information about the dust temperature and properties. The well-established detection strategy used for FLUOR and PIONIER can be employed with all instruments. The broad spectral capabilities of GRAVITY and MATISSE will allow for strong constraints on the dust properties through a better characterization of the SED shape and the potential detection of dust emission features (e.g., 3um and 10um silicate features). First steps toward a spectral characterisation of the excesses have been taken with PIONIER (Defrère et al. 2012, Ertel et al. 2014). Furthermore, a new survey in a wavelength range where the dust emits more strongly than in the H band reached with PIONIER will result in a larger sample to characterise and stronger statistical constraints on the incidence, properties, and evolution of the dust. It has been shown already, that the detection rate of hot exozodis is about twice as high in K band compared to H band at similar accuracy of the visibility measurements (Ertel et al. 2014). The K band beam combiner GRAVITY and the short wavelength channels of MATISSE (L, M bands) will be ideally suited for such surveys assuming a similar accuracy on the measurements as with PIONIER can be reached.

3.4 Critical technical requirements

There are three main challenges to be overcome for being able to fully characterise hot and warm exozodis with the VLTI:

- It is critical to reach an accuracy of ~1% on the single squared visibilities measured. This is necessary to reach a sufficient cumulative accuracy on the source visibilities to detect the excess and accurately measure the disc-to-star flux ratio. While this is readily reached with PIONIER and a specification for GRAVITY, it is only expected to be reached with MATISSE if a fringe tracker is used.
- Pointing (field rotation) dependent polarization effects in the VLTI optical path limit the absolute calibration of single PIONIER observations to ~3%. A specific observing strategy and additional calibration of this effect has to be employed to circumvent this limit (Ertel et al. 2014). This, however, requires observations of a large number of targets in a consistent way throughout a whole night which can only be carried out in visitor mode and puts significant limits on the flexibility of such observations. Correcting this effect on the instrument side (as expected for GRAVITY) or solving it on the VLTI side is critical for efficient and flexible high accuracy observations.
- To reach a sufficient cumulative accuracy on the measured source visibilities requires several measurements of one target. PIONIER has proven to be very efficient due to the simultaneous use of 4 telescopes (6 baselines). Still, several consecutive, calibrated measurements per target are necessary. Moreover, a potential variability of the hot emission has been detected on a timescale at least as short as one year (Ertel et al. 2016). The shortest timescale of these variations is not known. This variability calls at least for quasi-simultaneous observations of a target with all three instruments. To significantly increase the efficiency of the observations for both a survey for new systems and the characterisation of known systems, a fully simultaneous use of all three instruments (such as the "i-SHOOTER" concept) will be highly beneficial.

In addition to these critical requirements, further increasing the sensitivity to circumstellar excess would be highly beneficial for exozodi science with the VLTI. In particular, it would allow for surveys for exozodiacal dust in the Southern hemisphere with a sensitivity similar to that reached in the North with the LBTI and to detect systems only a few times brighter than our own zodiacal dust. The sensitivity of VLTI observations to faint circumstellar emission is currently limited by the ability to accurately measure and calibrate visibilities and to predict the stellar visibilities. These limitations can be overcome by nulling interferometry, where the stellar contribution is removed from the signal through destructive interference and only the extended circumstellar emission remains and can be detected directly. Such an instrument concept as introduced by Defrère et al. (this report) can improve the high contrast capabilities of the VLTI by one order of magnitude.

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