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

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Abstract Exo-zodiacal dust, exozodi for short, is warm  $(\sim 300 \text{K})$  or hot (up to  $\sim 2000 \text{K}$ ) dust found in the inner regions of planetary systems around main sequence stars. In analogy to our own zodiacal dust, it may be located in or near the habitable zone or closer in, down to the dust sublimation distance. The study of the properties, distribution, and evolution of exozodis can inform about the architecture and dynamics of the innermost regions of planetary systems, close to their habitable zones. On the other hand, the presence of large amounts of exo-zodiacal dust may be an obstacle for future space missions aiming to image Earth-like exoplanets. The dust can be the most luminous component of extrasolar planetary systems, but predominantly emits in the near- to mid-infrared where it is outshone by the host star. Interferometry provides a unique method of separating the dusty from the stellar emission. We discuss the prospects of exozodi observations with the

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Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena CA 91109-8099, USA next generation VLTI instruments and summarize critical instrument specifications.

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# 1 Introduction

The zodiacal dust in our Solar system is distributed between a few AU from the Sun down to  $\sim 4$  Solar radii (where it forms the F-corona) with a shallow surface density profile (Kimura and Mann, 1998; Hahn et al, 2002). In analogy to this dust, we call any dust near the habitable zone of other stars, or closer in, exozodiacal dust (or exozodi for short). In other systems we usually observe two distinct types of dust. Warm dust near the habitable zone is detected in the mid-infrared (Millan-Gabet et al, 2011; Mennesson et al, 2014; Ertel et al, 2018a), while hot dust very close to the star is detected in the near-infrared (Absil et al, 2006, 2013; Ertel et al, 2014). The connection between the two is not clear and the distinction might be largely observational. However, no correlation between the detections at the two wavelengths has been found so far, which would be expected from simply scaling the Solar system's dust distribution to the higher dust levels detectable in other systems. This suggests that other systems have diverse architectures and that the two species might or might not be directly connected.

The spatial dust distribution relates to its location of origin, production mechanism (asteroid collision, comet evaporation), and the dynamical interaction with the stellar radiation, wind, and magnetic field, as well as with potential planets. It thus traces the architecture and dynamics of the inner regions of planetary systems,





Fig. 1 Single (left) and combined (right) statistics from the FLUOR (red) and PIONIER (blue) sample. The top row shows the excess fraction with respect to the stellar spectral type, the middle row shows the same, but, in addition, separated for stars with and without a debris disk detected, and the bottom row shows the excess fraction for different spectral types and separated for stars younger and older than the median age in each spectral type bin. For details and interpretation see Ertel et al (2014).

in particular that of asteroids and comets (Bonsor et al, 2012, 2013, 2014; Lebreton et al, 2013; Faramaz et al, 2017) that are otherwise hard or impossible to study. On the other hand, the presence of large amounts of dust in or near the habitable zone of planetary systems may be an obstacle for the imaging detection and characterization of Earth-like, potentially habitable exoplanets (exo-Earths) by future space missions. The dust emission causes additional photon noise in the observations and clumps in the dust distribution, albeit potentially caused by interaction with planets, can be misinterpreted as actual planets given the limited angular resolution and signal-to-noise ratio expected from such observations (Defrère et al, 2010; Roberge et al, 2012; Stark et al, 2015). Even hot dust close to the star may significantly degrade coronagraphic performance at the level needed for exo-Earth imaging, as it produces emission that is more extended than the star and consequently cannot be perfectly suppressed. The study of the incidence rate of exo-zodiacal dust, its correlation with other, more accessible properties of the systems such as stellar luminosity, age, and the presence of an outer, cold reservoir of dust (debris disk, e.g. Eiroa et al 2013), and of the dust properties is critical for the success of such missions.

While rather small amounts of this dust can be relatively luminous due to its large surface and high temperature of few 100 to  $\sim 2000 \,\mathrm{K}$ , the emission of such warm or hot dust peaks in the near- to mid-infrared (nIR to mIR), where the emission of the host star dominates. The emission from the exozodis found so far produces an excess at the 1% level and below. Thus, detecting the dust requires spatially resolving the dust in order to disentangle its emission from that of the star. Because of the small angular scales (1 AU at a distance of 10 pc corresponds to an angular separation from the host star of 0.1 arcsec), only interferometry is currently able to reach the required angular resolution. Near-IR interferometry has produced the largest number of detected exozodis to date. The VLTI instrument PIONIER has been particularly efficient in surveying a large number of stars. The broad wavelength coverage of the second-generation suite of VLTI instruments (and PIONIER) is particularly well suited for the characterization of exozodis. In this article, we discuss the prospects of observing exo-zodiacal dust with these instruments. We briefly summarize the past and current observational efforts to study exozodis with focus on interferometric observations (Sect. 2). For a detailed review of the field of exo-zodiacal dust, we refer to Kral et al (2017). We explain the method used to detect exozodis with optical long baseline interferometry (Sect. 3) which is the relevant method for all current and near future VLTI instruments. In Sect. 4, we discuss the prospects of using the second generation VLTI instruments to further study exo-zodiacal dust. The critical technical requirements of instruments for exozodi observations are reviewed in Sect. 5. We present our conclusions in Sect. 6.

### 2 Recent observational success

The first detection of faint nIR excess at the 1% level around a main sequence star was reported for Vega by Absil et al (2006). It was achieved using the FLUOR beam combiner on the CHARA array. Motivated by this detection, survey observations were carried out using CHARA/FLUOR and the PIONIER beam combiner on the VLTI that produced the first statistical samples of detected exozodis (Absil et al 2013; Ertel et al 2014; Fig. 1). As of today, more than 200 stars have systematically been surveyed in the nIR with a detection rate of ~20% (Nuñez et al 2017; Marion et al, subm.).



Fig. 2 Detection strategy of hot exo-zodiacal dust using near-infrared optical interferometry.

Follow-up observations of a sample of detections have demonstrated the repeatability of the observations and revealed first signs of significant variability of the excesses (Nuñez et al 2017; Ertel et al 2016). These observations provide detailed information about the presence of exozodis and their correlation with various properties of the host systems, and motivated and informed several theoretical studies (Bonsor et al 2012, 2013, 2014; Lebreton et al 2013; Rieke et al 2016; Faramaz et al 2017; McKinley et al, in prep.). In parallel, first excesses from warm dust near the habitable zone of other stars were detected using mIR nulling interferometry on the MMT (Stock et al, 2010) and the Keck Interferometric Nuller (Millan-Gabet et al, 2011; Mennesson et al, 2014). Combining data from both nIR and mIR interferometric observations provide particularly strong constraints of the dust properties and location (Defrère et al, 2011; Lebreton et al, 2013; Kirchschlager et al, 2017). Recently, the Large Binocular Telescope Interferometer (LBTI) has surveyed a sample of  $\sim 40$  nearby main sequence stars for habitable zone dust at unprecedented sensitivity (Ertel et al 2018a,b; Ertel et al, in prep.) and achieved a detection rate similar to those in the nIR. Strong constraints on the scattered light content of hot exozodi systems have been provided by parts per million accuracy polarimetric observations (Marshall et al, 2016). Additional constraints have been provided by ground and space based spectroscopic observations (e.g., Chen et al 2006; Lisse et al 2007; Ballering et al 2014; Lisse et al, in prep.) and by studying WISE data of a large sample of stars to constrain the incidence rate of exozodis at the bright end of their luminosity function (Kennedy and Wyatt, 2013).

# 3 Detection using optical long baseline interferometry

By far the largest number of exozodis has been detected using optical long baseline interferometry in the nearinfrared 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 disk 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 disk-to-star flux ratio can be measured as half the visibility deficit (Fig. 2). The fact that the star is almost unresolved is important, because in this case the uncertain stellar diameter has very little impact on the prediction of the visibilities from the star alone and thus the visibility deficit can be measured at high accuracy.

Due to the small disk-to-star 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. PIO-NIER 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 disk as the cause for the detected excess (Marion et al, 2014).

# 4 New opportunities with VLT and LBT interferometry

So far, most detections were achieved only in one band. The large spectral separation of the H/K and the N bands and different inner working angles and sensitivities of the instruments used make it difficult to connect detections in the two bands or trace the excess from one band to the other. PIONIER observations have provided a small spectral dispersion across the H band, but the spectral separation of the channels is too small to put strong constraints on the spectral shape of the excesses. Only the characterization of exozodis can answer the three most urgent key questions beyond the frequency and abundance of massive dust systems:

- What is the connection between the warm and hot dust? This is important because most systems so far have been detected in the nIR, 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, 2014), but contradictory results were found by Marion et al (subm.) based on a different strategy and a larger sample.

- Where is the dust located? Detailed temperature information can only be derived from multi-wavelength observations that sample well the relevant parts of the dust's spectral energy distribution (nIR to mIR). In addition, spatial information may be derived from observations at suitable wavelengths and baselines (Kirchschlager et al, 2018). The dust location gives critical insight into the architecture and dynamics of the underlying planetary system. Furthermore, the dust location relative to the habitable zone is critical information for future exo-Earth imaging missions.
- What are the dust properties? The dust is detected as thermal emission in the mIR and as a potential combination of thermal emission and scattered light measured in the nIR. 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 visible where future exo-Earth imaging missions will operate.

The second-generation VLTI instruments GRAV-ITY 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 the nIR to mIR wavelength range (Fig. 3). 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 GRAV-ITY 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.,  $3 \,\mu m$  and  $10 \,\mu m$  silicate features). First steps toward a spectral characterization 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 PIO-NIER will result in a larger sample to characterize 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



Fig. 3 Wavelength coverage of the second-generation VLTI instruments (and PIONIER) compared to the wavelength range in which the emission from hot and warm exo-zodiacal dust is expected to peaks. The dust emission is approximated by a modified blackbody (a blackbody multiplied by  $\lambda^{-2}$ ), which represents very small grains as suggested at least for hot dust by PIONIER observations at multiple wavelengths (Ertel et al, 2014). 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 characterization of scattered light is particularly critical for the understanding of the impact of the dust on exo-Earth imaging missions.

can be reached on a statistically significant number of stars.

First observations with GRAVITY during science verification and open time have demonstrated the required accuracy to detect exozodis and demonstrated the wealth of information contained in the low resolution spectra produced in the K band (Defrère et al, in prep.).

### **5** Critical technical requirements

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

- It is critical to reach an accuracy of at least 1% on the individual measurements of the calibrated squared visibility. This is necessary to reach a sufficient cumulative accuracy on the source visibilities to detect the excess detected in available observations and accurately measure the disk-to-star flux ratio. Previous detections at the 1% level have been achieved in both the near-infrared and the mid-infrared (see Sect. 2). While the emission from blackbody grains emitting in the near-infrared at temperatures <2000 K is expected to increase to-</p>

ward longer wavelengths, this is not seen in spectrally dispersed PIONIER observations (although the constraints on the slope are weak due to the small wavelength coverage). The presence of very small grains would explain this (Fig. 3). As a consequence, the emission is not expected to be above a few percent at any wavelength. While this sensitivity is readily reached with PIONIER and has been demonstrated for GRAVITY, it is not expected to be reached with MATISSE without the use of a fringe tracker. MATISSE is thus currently limited to observing very extreme systems with massive warm dust detections (e.g., Lisse et al 2007, 2008; Olofsson et al 2012).

- 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 done with 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 in order to avoid corruption of the obtained SED data by excess variability between the different observations. To significantly increase the efficiency of the observations for both a survey for new systems and the characterization of known systems, a fully simultaneous use of all three instruments (such as the "i-SHOOTER" concept, to use GRAVITY, MATISSE, and PIONIER simultaneously to obtain H to N band data of a target at the same time) 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 exo-zodiacal 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. In the near-infrared, 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. This is less critical when aiming to detect dust closer to the habitable zone of a system in the midinfrared, because lower angular resolution is sufficient. The star is then even less resolved and the impact of its uncertain diameter thus further reduced. In addition, nulling interferometry can be used to remove the stellar light in addition to spatially separating it from the disk emission. An instrument employing this technique has been introduced as the hi-5 concept by Defrère et al (2018) and can improve the high contrast capabilities of the VLTI by one order of magnitude. Moreover, such

an instrument would be the first to search for faint habitable zone dust in the Southern hemisphere, critically extending the sample of stars that can be searched.

## 6 Conclusions

The multi-wavelength capabilities of the second generation VLTI instruments will be vital to further study exo-zodiacal dust. However, in particular for MATISSE the visibility accuracy needed to detect exozodis is not expected to be readily met at the time of commissioning. Additional effort will be needed to enable the exploitation of the VLTI capabilities and to retain its leading role in the characterization of exozodis in the near future. The gain of one order of magnitude in highcontrast capabilities, as it could be achieved with a nulling interferometer (hi-5 concept), would allow for a survey for habitable zone dust at the extreme efficiency demonstrated by PIONIER and at the accuracy currently only reached with lower efficiency and on a limited sample of stars in the Northern hemisphere.

### References

- Absil O, di Folco E, Mérand A, Augereau JC, Coudé du Foresto V, Aufdenberg JP, Kervella P, Ridgway ST, Berger DH, ten Brummelaar TA, Sturmann J, Sturmann L, Turner NH, McAlister HA (2006) Circumstellar material in the ¡AS-TROBJ¿Vega¡/ASTROBJ¿ inner system revealed by CHARA/FLUOR. A&A452:237–244, DOI 10.1051/ 0004-6361:20054522, arXiv:astro-ph/0604260
- Absil O, Defrère D, Coudé du Foresto V, Di Folco E, Mérand A, Augereau JC, Ertel S, Hanot C,

Kervella P, Mollier B, Scott N, Che X, Monnier JD, Thureau N, Tuthill PG, ten Brummelaar TA, McAlister HA, Sturmann J, Sturmann L, Turner N (2013) A near-infrared interferometric survey of debris-disc stars. III. First statistics based on 42 stars observed with CHARA/FLUOR. A&A555:A104, DOI 10.1051/0004-6361/201321673, 1307.2488

- Ballering NP, Rieke GH, Gáspár A (2014) Probing the Terrestrial Regions of Planetary Systems: Warm Debris Disks with Emission Features. ApJ793:57, DOI 10.1088/0004-637X/793/1/57, 1407.7547
- Bonsor A, Augereau JC, Thébault P (2012) Scattering of small bodies by planets: a potential origin for exozodiacal dust? A&A548:A104, DOI 10.1051/ 0004-6361/201220005, 1209.6033
- Bonsor A, Raymond SN, Augereau JC (2013) The short-lived production of exozodiacal dust in the aftermath of a dynamical instability in planetary systems. MNRAS433:2938–2945, DOI 10.1093/mnras/ stt933, 1306.0592
- Bonsor A, Raymond SN, Augereau JC, Ormel CW (2014) Planetesimal-driven migration as an explanation for observations of high levels of warm, exozodiacal dust. MNRAS441:2380–2391, DOI 10.1093/ mnras/stu721, 1404.2606
- Chen CH, Sargent BA, Bohac C, Kim KH, Leibensperger E, Jura M, Najita J, Forrest WJ, Watson DM, Sloan GC, Keller LD (2006) Spitzer IRS Spectroscopy of IRAS-discovered Debris Disks. ApJS166:351-377, DOI 10.1086/505751, arXiv:astro-ph/0605277
- Defrère D, Absil O, den Hartog R, Hanot C, Stark C (2010) Nulling interferometry: impact of exozodiacal clouds on the performance of future lifefinding space missions. A&A509:A9, DOI 10.1051/ 0004-6361/200912973, 0910.3486
- Defrère D, Absil O, Augereau JC, di Folco E, Berger JP, Coudé du Foresto V, Kervella P, Le Bouquin JB, Lebreton J, Millan-Gabet R, Monnier JD, Olofsson J, Traub W (2011) Hot exozodiacal dust resolved around Vega with IOTA/IONIC. A&A534:A5, DOI 10.1051/0004-6361/201117017, 1108.3698
- Defrère D, Lebreton J, Le Bouquin JB, Lagrange AM, Absil O, Augereau JC, Berger JP, di Folco E, Ertel S, Kluska J, Montagnier G, Millan-Gabet R, Traub W, Zins G (2012) Hot circumstellar material resolved around ¡ASTROBJ¿ $\beta$  Pic¡/ASTROBJ¿ with VLTI/PIONIER. A&A546:L9, DOI 10.1051/ 0004-6361/201220287, 1210.1914
- Defrère D, Absil O, Berger JP, Boulet T, Danchi WC, Ertel S, Gallenne A, Hénault F, Hinz P, Huby E, Ireland M, Kraus S, Labadie L, Le Bouquin JB, Martin G, Matter A, Mérand A, Mennesson B, Minardi S,

Monnier J, Norris B, Orban de Xivry G, Pedretti E, Pott JU, Reggiani M, Serabyn E, Surdej J, Tristram KRW, Woillez J (2018) The path towards high-contrast imaging with the VLTI: the Hi-5 project. ArXiv e-prints 1801.04148

- Eiroa C, Marshall JP, Mora A, Montesinos B, Absil O, Augereau JC, Bayo A, Bryden G, Danchi W, del Burgo C, Ertel S, Fridlund M, Heras AM, Krivov AV, Launhardt R, Liseau R, Löhne T, Maldonado J, Pilbratt GL, Roberge A, Rodmann J, Sanz-Forcada J, Solano E, Stapelfeldt K, Thébault P, Wolf S, Ardila D, Arévalo M, Beichmann C, Faramaz V, González-García BM, Gutiérrez R, Lebreton J, Martínez-Arnáiz R, Meeus G, Montes D, Olofsson G, Su KYL, White GJ, Barrado D, Fukagawa M, Grün E, Kamp I, Lorente R, Morbidelli A, Müller S, Mutschke H, Nakagawa T, Ribas I, Walker H (2013) DUst around NEarby Stars. The survey observational results. A&A555:A11, DOI 10.1051/0004-6361/201321050, 1305.0155
- Ertel S, Absil O, Defrère D, Le Bouquin JB, Augereau JC, Marion L, Blind N, Bonsor A, Bryden G, Lebreton J, Milli J (2014) A near-infrared interferometric survey of debris-disk stars. IV. An unbiased sample of 92 southern stars observed in H band with VLTI/PIONIER. A&A570:A128, DOI 10.1051/0004-6361/201424438, 1409.6143
- Ertel S, Defrère D, Absil O, Le Bouquin JB, Augereau JC, Berger JP, Blind N, Bonsor A, Lagrange AM, Lebreton J, Marion L, Milli J, Olofsson J (2016) A nearinfrared interferometric survey of debris-disc stars. V. PIONIER search for variability. A&A595:A44, DOI 10.1051/0004-6361/201527721, 1608.05731
- Ertel S, Defrère D, Hinz P, Mennesson B, Kennedy GM, Danchi WC, Gelino C, Hill JM, Hoffmann WF, Rieke G, Shannon A, Spalding E, Stone JM, Vaz A, Weinberger AJ, Willems P, Absil O, Arbo P, Bailey VP, Beichman C, Bryden G, Downey EC, Durney O, Esposito S, Gaspar A, Grenz P, Haniff CA, Leisenring JM, Marion L, McMahon TJ, Millan-Gabet R, Montoya M, Morzinski KM, Pinna E, Power J, Puglisi A, Roberge A, Serabyn E, Skemer AJ, Stapelfeldt K, Su KYL, Vaitheeswaran V, Wyatt MC (2018a) The HOSTS Survey – Exozodiacal Dust Measurements for 30 Stars. AJ155:194, DOI 10.3847/1538-3881/aab717, 1803.11265
- Ertel S, Kennedy GM, Defrère D, et al (2018b) The HOSTS Survey for Exo-zodiacal Dust: Preliminary results and future prospects, proceedings SPIE, in press
- Faramaz V, Ertel S, Booth M, Cuadra J, Simmonds C (2017) Inner mean-motion resonances with eccentric planets: a possible origin for exozodiacal dust

clouds. MNRAS465:2352–2365, DOI 10.1093/mnras/ stw2846, 1611.02196

- Hahn JM, Zook HA, Cooper B, Sunkara B (2002) Clementine Observations of the Zodiacal Light and the Dust Content of the Inner Solar System. Icarus158:360–378, DOI 10.1006/icar.2002. 6881, astro-ph/0204111
- Kennedy GM, Wyatt MC (2013) The bright end of the exo-Zodi luminosity function: disc evolution and implications for exo-Earth detectability. MNRAS433:2334–2356, DOI 10.1093/mnras/stt900
- Kimura H, Mann I (1998) Brightness of the solar Fcorona. Earth, Planets, and Space 50:493–499
- Kirchschlager F, Wolf S, Krivov AV, Mutschke H, Brunngräber R (2017) Constraints on the structure of hot exozodiacal dust belts. MNRAS467:1614–1626, DOI 10.1093/mnras/stx202, 1701.07271
- Kirchschlager F, Wolf S, Brunngräber R, Matter A, Krivov AV, Labdon A (2018) Modelling of midinfrared interferometric signature of hot exozodiacal dust emission. MNRAS473:2633–2638, DOI 10.1093/ mnras/stx2515, 1709.08514
- Kral Q, Krivov AV, Defrere D, van Lieshout R, Bonsor A, Augereau JC, Thebault P, Absil O, Ertel S (2017)
  Exozodiacal clouds: Hot and warm dust around main sequence stars. ArXiv e-prints 1703.02540
- Lebreton J, van Lieshout R, Augereau JC, Absil O, Mennesson B, Kama M, Dominik C, Bonsor A, Vandeportal J, Beust H, Defrère D, Ertel S, Faramaz V, Hinz P, Kral Q, Lagrange AM, Liu W, Thébault P (2013) An interferometric study of the Fomalhaut inner debris disk. III. Detailed models of the exozodiacal disk and its origin. A&A555:A146, DOI 10.1051/0004-6361/201321415, 1306.0956
- Lisse CM, Beichman CA, Bryden G, Wyatt MC (2007) On the Nature of the Dust in the Debris Disk around HD 69830. ApJ658:584–592, DOI 10.1086/511001, arXiv:astro-ph/0611452
- Lisse CM, Chen CH, Wyatt MC, Morlok A (2008) Circumstellar Dust Created by Terrestrial Planet Formation in HD 113766. ApJ673:1106–1122, DOI 10.1086/523626, 0710.0839
- Marion L, Absil O, Ertel S, Le Bouquin JB, Augereau JC, Blind N, Defrère D, Lebreton J, Milli J (2014) Searching for faint companions with VLTI/PIONIER. II. 92 main sequence stars from the Exozodi survey. A&A570:A127, DOI 10.1051/ 0004-6361/201424780, 1409.6105
- Marshall JP, Cotton DV, Bott K, Ertel S, Kennedy GM, Wyatt MC, del Burgo C, Absil O, Bailey J, Kedziora-Chudczer L (2016) Polarization Measurements of Hot Dust Stars and the Local Interstellar Medium. ApJ825:124, DOI 10.3847/0004-637X/825/

2/124, 1604.08286

- Mennesson B, Millan-Gabet R, Serabyn E, Colavita MM, Absil O, Bryden G, Wyatt M, Danchi W, Defrère D, Doré O, Hinz P, Kuchner M, Ragland S, Scott N, Stapelfeldt K, Traub W, Woillez J (2014) Constraining the Exozodiacal Luminosity Function of Main-sequence Stars: Complete Results from the Keck Nuller Mid-infrared Surveys. ApJ797:119, DOI 10.1088/0004-637X/797/2/119
- Millan-Gabet R, Serabyn E, Mennesson B, Stark CC, Ragland S, Hrynevych M, Woillez J, Stapelfeldt K, Bryden G, Colavita MM, Booth AJ (2011) Exozodiacal Dust Levels for Nearby Main-sequence Stars: A Survey with the Keck Interferometer Nuller. ApJ734:67, DOI 10.1088/0004-637X/734/1/ 67, 1104.1382
- Nuñez PD, Scott NJ, Mennesson B, Absil O, Augereau JC, Bryden G, ten Brummelaar T, Ertel S, Coude du Foresto V, Ridgway ST, Sturmann J, Sturmann L, Turner NJ, Turner NH (2017) A near-infrared interferometric survey of debris-disk stars. VI. Extending the exozodiacal light survey with CHARA/JouFLU. ArXiv e-prints 1709.01655
- Olofsson J, Juhász A, Henning T, Mutschke H, Tamanai A, Moór A, Ábrahám P (2012) Transient dust in warm debris disks. Detection of Ferich olivine grains. A&A542:A90, DOI 10.1051/ 0004-6361/201118735, 1204.2374
- Rieke GH, Gáspár A, Ballering NP (2016) Magnetic Grain Trapping and the Hot Excesses around Earlytype Stars. ApJ816:50, DOI 10.3847/0004-637X/ 816/2/50, 1511.04998
- Roberge A, Chen CH, Millan-Gabet R, Weinberger AJ, Hinz PM, Stapelfeldt KR, Absil O, Kuchner MJ, Bryden G (2012) The Exozodiacal Dust Problem for Direct Observations of Exo-Earths. PASP124:799–808, DOI 10.1086/667218, 1204.0025
- Stark CC, Roberge A, Mandell A, Clampin M, Domagal-Goldman SD, McElwain MW, Stapelfeldt KR (2015) Lower Limits on Aperture Size for an ExoEarth Detecting Coronagraphic Mission. ApJ808:149, DOI 10.1088/0004-637X/808/2/149, 1506.01723
- Stock ND, Su KYL, Liu W, Hinz PM, Rieke GH, Marengo M, Stapelfeldt KR, Hines DC, Trilling DE (2010) The Structure of the  $\beta$  Leonis Debris Disk. ApJ724:1238–1255, DOI 10.1088/0004-637X/724/2/1238, 1010.0003