Astro2020 Science White Paper

Interplanetary dust around main sequence stars: origin, magnitude, and implications for exoplanet habitability searches

Thematic Areas: ☒ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Bertrand Mennesson
Institution: Jet Propulsion Laboratory, California Institute of Technology
Email: Bertrand.mennesson@jpl.nasa.gov
Phone: 818-354-0494

Co-authors:
G. Kennedy (Univ. of Warwick), S. Ertel (Univ. of Arizona), M. Wyatt (Univ. of Cambridge), D. Defrère (Liege Space Center), J. Debes (STScI), C. Stark (STScI), J. Kasdin (Princeton), B. Macintosh (Stanford), P. Hinz (Univ. of Arizona), V. Bailey (JPL), K. Stapelfeldt (NASA/JPL), D. Mawet (Caltech/JPL), N. Scott (NASA/Ames), A. Roberge (NASA/GSFC), C. Lisse (JHU/APL), W. Lyra (JPL), Y. Hasegawa (JPL), A. Gaspar (Univ. of Arizona), W. Danchi (NASA/GSFC), R. Millan-Gabet (GMT), C. Haniff, (Univ. of Cambridge), A. Skemer (UCSC), E. Serabyn (JPL), J. Stone(Univ. of Arizona), G. Bryden (JPL)

Co-signers: T. D. Robinson (Northern Arizona Univ.), S. Ridgway (NOAO), A. Moro-Martín (STScI), D. Ardila (JPL), D. Buzasi(FGCU), S. Seager (MIT), J.C. Augereau (IPAG), S. Ragland (WMKO), A. Weinberger (Carnegie DTM), G. van Belle (Lowell Obs.)

Abstract: The brightness and spatial distribution of warm (≳200K) dust structures located within a few AU of main sequence stars—commonly referred to as exozodiacal dust or "exozodi"—reflect present dust sources (comets, asteroids), as well as sinks (Poynting-Robertson drag, radiation pressure), and perturbations (collisions, evaporation, planets). As such, exozodi observations provide unique insights into the inner regions of individual planetary systems, as well as their current dynamical state and formation history. However, only a dozen systems with bright exozodi have been spatially resolved to date and their basic physical properties remain vastly unknown. We motivate and identify here the main instrumental / observational advances required to gain further insights into the origins of exozodi dust clouds and better understand their impact on planetary habitability and habitability searches.

This white paper focuses on the inner regions of debris disks and on observational aspects. Separate complementary papers are being submitted regarding the outer cold regions of debris disks (J. Debes et al.), the modeling of debris disks evolution (A. Gaspar et al.) and disks thermal emission (Su et al.).

1. What is the origin of exozodiacal dust?

The solar system zodiacal cloud contains a population of small (~1–100 μm) warm dust grains located within the asteroid belt, extending from <0.1 AU to ~3.3 AU. The COBE Diffuse Infrared Background Experiment measured zodiacal light from 1.25–240 μm, enabling modeling of brightness distribution, grain size distribution, temperature, and optical depth radial profiles with high accuracy.[1,2] While its optical depth is only 10^{-7} at 1 AU and its total mass estimated to only a few 10^{-9} Earth mass—equivalent to a 15 km diameter asteroid—the zodiacal cloud integrated flux dominates that of any planet in the solar system in both scattered sunlight and thermal emission. Solar system zodiacal dust is believed to originate from asteroid collisions and evaporation/break-up of comets as they approach the Sun. While the relative contributions of asteroids and comets is still under debate, and difficult to establish from within the disk, recent progress has suggested that it may be dominated by spontaneous disruption of Jupiter family comets.[3] Similarly, "exozodi" dust refers to the inner (≲5 AU) warmer (≳200 K) part of circumstellar debris disks found around main sequence stars, including, but not restricted to, the region where terrestrial planets form, and where we might see the signature of "exo-comets" and "exo-asteroids." While the term "exozodi" suggests a dust component analogous to that of the inner solar system, it is worth emphasizing that exozodi may be very different in terms of density levels, spatial distributions, compositions, and origins. The dozen systems characterized in some detail so far,[4,5,6,7] are all much brighter than the solar system zodiacal cloud, with brightness levels >100 "zodis," i.e., habitable zone (HZ) dust densities at least 100 times higher than in the solar system.

There are essentially three main scenarios invoked for the generation of exozodi dust: (1) in-situ random collision(s) between parent bodies that normally reside where the dust is observed[8]; (2) inward transport of dust from an outer Kuiper-belt-like region via Poynting-Robertson (P-R) drag[9,10]; and (3) inward transport of comets scattered from an outer Kuiper-belt-like region or from more distant regions via a dynamical instability.[11] The latter two scenarios predict significantly different total brightness levels and optical depth radial profiles in the inner (exozodi) region (Figure 1). Put simply, optical depth levels significantly above P-R drag expectations point to dust delivery via comet scattering,[12] while optical depth levels significantly lower than P-R drag point toward dynamical interactions with planets.[13]

For unresolved observations, correlating a broad-range of exozodi brightness levels with basic stellar properties (mass, age, known existence of outer cold dust) would already be very informative, as different dust production mechanisms are expected to produce distinct correlation strengths and exozodi luminosity functions[6] (Section 2). The next step to inform exozodi origin in individual systems would be to spatially resolve the radial and azimuthal structures of exozodi, as well as other components that may be at stake in shaping them: outer disk belts and planets (Section 3). *Exozodi dust* spectral characterization over a broad range of visible to mid-infrared (IR) wavelengths will also help distinguish between in-situ dust formation mechanisms (e.g., Ref. 14) and inward delivery from regions located beyond the snow line (e.g., Ref. 15). In addition, basic dust properties (e.g., density profile and size distribution) cannot be derived from measurements over a narrow wavelength range. For instance, the exozodi total brightness or its spatial profile at visible or shorter

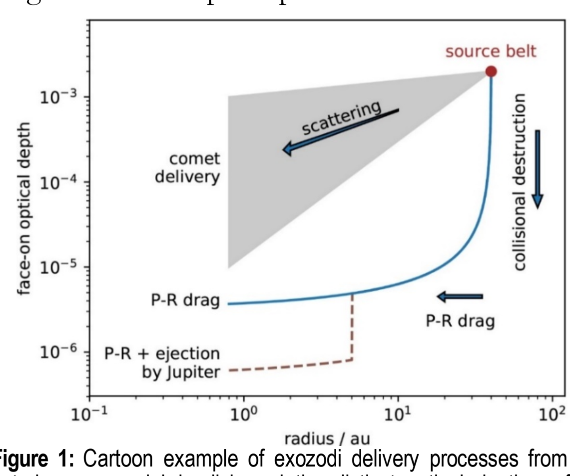

Figure 1: Cartoon example of exozodi delivery processes from an exterior source debris disk and the distinct optical depth profiles expected. The dust level is depleted by destructive collisions as it spirals in under P-R drag (blue line) and can be additionally depleted as it passes planets (dotted line). Conversely, cometary scattering can result in a very wide range of dust levels in the habitable zone, including higher optical depth regions (gray swath) incompatible with P-R drag alone. Image courtesy of G. Kennedy, Univ. of Warwick.

IR wavelengths cannot be reliably extrapolated from mid-IR measurements alone (Sections 4 & 5). This point is illustrated by the intriguing detection of ~1% near-IR excesses around ~20% of main sequence stars,[1619] most of them showing no mid-IR excess. We describe hereafter some key observables promising to further constrain the origin of exozodi and better understand its impact on exoplanet habitability searches. Required observational capabilities are given in Section 6.

2. What is the exozodi luminosity function?

The exozodi "luminosity function," i.e., the distribution of—spatially integrated—exozodi flux levels relative to the star, is a powerful observable to constrain the origin of exozodi, especially if measured over a broad range of wavelengths. E.g., assuming pure in-situ formation[6]—and forcing that model to match the small fraction of stars with extremely bright exozodi detected by WISE—would result in the 12 μm luminosity function model shown in Figure 2 (dashed curve). Measuring the entire exozodi luminosity function down to faint exozodi fluxes in the visible to mid-IR range—where warm exozodi is detectable—would confront the local collisions model and others (e.g., P-R drag, comets, and planet interactions) with actual observations. Repeating such measurements over a wide range of stellar parameters, planetary systems and outer debris belts characteristics will narrow down the relative contributions of these different exozodi origins. However, for such population-type modeling to be meaningful, hundreds of exozodi detections are required, down to faint dust levels.

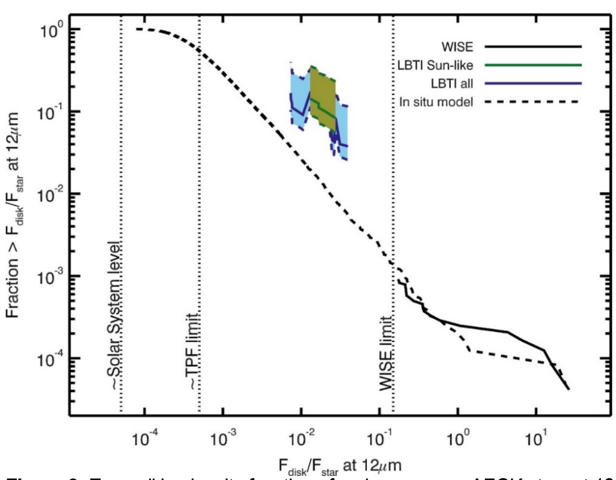

Figure 2: Exozodi luminosity function of main sequence AFGK stars at 12 μm. The dashed line shows the luminosity function predicted by a pure in-situ dust formation model, forcing it to match the fraction of extreme exozodi detected by WISE.[6] The blue/green swath with shaded uncertainty ranges corresponds to the LBTI exozodi survey results. Faint exozodi are more common than expected if they all arose from in-situ collisions, suggesting that some exozodi are delivered from more distant regions by P-R drag and/or by comets.

<u>*Current state of the art and limitations.*</u> Current space-based infrared telescopes cannot spatially distinguish the exozodi region from the central star. They rely instead on spectral energy distribution (SED) excess measurements, which require careful calibration and accurate subtraction of the model-dependent stellar SED. As a result, Spitzer InfraRed Spectrometer exozodi detection limits are typically 100 zodis at 24 μm, and 1,000 zodis at 10 μm, the wavelength most sensitive to HZ dust. Out of 203 FG main sequence stars observed by Spitzer, only two showed an excess in the short wavelength band (8.5–12 μm).[20,21] *To detect and measure the brightness of exozodi disks around a large number of sunlike stars, significantly lower dust density levels must be accessed, meaning that the dust-emitting region needs to be spatially resolved from the star.* In the mid-IR, this calls for nulling interferometry, an observational challenge tackled successively by the Multi Mirror Telescope Nuller,[22,23] the Keck Interferometer (KI) Nuller,[24,25,26,27] and the Large Binocular Telescope Interferometer (LBTI).[28,29] The LBTI exozodi key science survey[30,31] has reached the best sensitivity with typical detection limits of 60 zodis for early type stars (A-F5) and ~150 zodis for sunlike stars,[7] both at 11 μm. While these LBTI results provide a significant gain (~5×) over KI results, current detection limits are still far above solar zodi density levels, and the sample size—about 40 stars for either KI or LBTI—remains small for statistically meaningful correlation studies.

3. Can exozodi be used to infer the presence (or absence) of planets?

Extended debris disks' inner cavities, warps, offsets, non-axisymmetric features, spirals, clumps and separated rings revealed in scattered light images[32] (and/or thermal emissions) of μm- to millimeter-sized dust particles are commonly believed to be signposts of existing planets (e.g., Ref. 33). *Is it really the case?* And if comparable structures exist in the inner exozodi region, do they indeed correlate with the presence or absence of planets (e.g., Refs. 11, 34), *and in which case*? To help establish the 'ground truth' of disk-planet interactions, spatially resolved images of debris disks of variable dust levels and any exoplanets embedded in them must be obtained for a broad range of planetary masses and separations (see white paper led by J. Debes). While there will always be ways of making exozodi structures without planets, e.g., radial structure from sublimation, the association with planets may be more frequent in some cases. This could happen in the transport-dominated regime, i.e., at dust density levels low enough that dust structures induced by mean motion resonances should become more prominent than those created by possible planet-free scenarios (e.g., clumps from collisions, self-shadowing and other dust-gas interaction found in younger denser systems). It may also be possible to empirically determine which observed exozodi features (e.g., clump orbital motion, grain size distribution) correlate with the presence of planets. Measuring such correlations would make it possible to truly use dust disk observations as an indirect planet detection technique and reveal the presence of planets too small and/or faint to image directly.

Current state of the art and limitations. A connection between debris disk features and the presence of a massive perturbing planet was successfully demonstrated with the very extended bright asymmetric debris disk observed around Beta Pic[35,36] and the self-luminous giant planet subsequently imaged around it.[37] While this extraordinary case remains one of a kind, the connection between debris disks and planets has also been seen in several of the currently known, directly imaged planetary systems, such as HR 8799, β Pictoris, HD 95086, HD 106906, Fomalhaut, and 51 Eridani (see, e.g., Ref. 38 for a recent review). Using the largest sample systems with cold outer dust belts directly surveyed for long-period giant planets to date, Meshkat et al.[39] recently found that the occurrence rate of such planets in dusty systems is about 10 times higher than in dust-free systems (at current detection limits), providing tentative empirical evidence for a connection between the presence of planets and the existence of a bright extended debris disks.

However, to further establish and understand this connection, the radial and azimuthal structures of debris disks must be observed, and correlated with the presence/absence of many more planets than presently detected. *To spatially resolve exozodi spatial structures around mature stars—only detectable in reflected light or thermal emission—and at the same time directly reveal any perturbing planets embedded in them, observations should reach detection limits per resolution element ranging from ~10^{-9} in the visible to ~10^{-8} in the near-IR and ~10^{-5} in the mid-IR, all at separations ~0.1–0.2".* These contrast requirements are about 100 times more stringent than current capabilities.[40,41,42]

4. What is the origin of the hot excess phenomenon?

Maybe one of the most intriguing result of high angular resolution observational astronomy in the last ~10 years is the resolved interferometric detection of ~1% near-IR (H- and K-band) excesses around a significant fraction (~20%) of nearby main sequence stars (e.g., Refs. 17, 18, 19, 20, 43, 44). Because excesses are resolved with ~30 m baselines, they must arise from regions located >~5 stellar radii away from the star, or—if only marginally resolved—be even brighter than we measure. While an extended stellar atmosphere phenomenon (or stellar companions[45]) cannot be completely ruled out in all systems, it has never been reported around these stars, and a dust origin remains most likely. Because the near-IR excesses show no polarization signature (suggesting a thermal origin[46]) and are no longer detected at shorter baselines (Ref. 47 and unpublished results of Palomar 200" nulling survey of hot excess stars), most of the dust responsible for the excess must lie close to the ~1,500–2,000K sublimation radius around the star, i.e., 0.03–0.15 AU depending on spectral type. These near-IR excesses also have generally no mid-IR counterpart detected by interferometry,[30] pointing to grains small enough to elude detection at longer IR wavelengths, i.e., μm-sized or smaller (e.g., Refs. 48, 49).

Local production of massive amounts of dust in a very close asteroid belt is impractical because the lifetime of observed dust particles under the effect of collisions is far shorter than the typical stellar age.[10] Production in catastrophic events is unlikely due to the high occurrence rate of hot excesses. Nonetheless, there must be an efficient mechanism to replenish the dust at an extreme rate as it is rapidly removed from the system due to the coupled effect of collisions and stellar radiation pressure.

Production in an outer asteroid belt or Kuiper belt analog and delivery through P-R drag is one scenario, but requires efficient dust trapping mechanisms to partly mitigate the requirement for very high replenishment rates [e.g., realistic dynamics of sublimating dust grains,[50] or magnetic trapping of nanograins[51,52,53] (debated by Ref. 54)]. Delivery of the dust due to high cometary activity in these systems similar to the Falling Evaporating Bodies phenomenon observed in the β Pictoris inner disk[55,56] or the solar system Late Heavy Bombardment[57] is a promising alternative. In this case, a durable dust replenishment over Gyr ages may be possible.[3,9,58,59] This scenario may also cause the episodic dust production and excess variability observed in some systems.[60,61] If the hot dust phenomenon is indeed a signpost of ongoing bombardment by large cometary bodies that can potentially strip a planetary atmosphere or replenish it with volatiles, its detection would have serious implications for the architecture of exoplanetary systems and habitability of any inner rocky planets.

Current state of the art and limitations. A major open question is whether the hot dust component inferred in the near-IR can be used to trace a fainter cooler component of grains extending into the HZ, as suggested in the case of Fomalhaut.[48] Unfortunately, the current near-IR hot excess detections suffer from limited dynamic range, temporal and spatial (u-v plane) coverage. As a result, the hot dust location, as well as its temporal variability remain poorly constrained. If ~20% of main sequence stars show a hot excess at the 1% level, what fraction will at a 0.1% detection threshold? Improving dynamic range, - i.e, interferometric visibility accuracy- and extending (u,v) coverage are the key observational improvements required.. Extending the spectral coverage from 1–2 μm to 3–5 μm would also be very informative to confirm the "small grains thermal emission scenario" and bridge the gap between near-IR and mid-IR measurements.

5. What is the impact of exozodi on the science yield of future exo-Earth direct imaging missions?

Exozodi dust is a double-edged sword. Bright exozodi structures can provide key information about the dynamical processes at play in other systems and may reveal the presence of otherwise undetectable planets. But they may also represent a significant impediment to direct imaging and spectral characterization of planets around other stars, particularly faint Earth-like exoplanets orbiting in the HZ. Considering for instance a 4 m telescope viewing a Sun-Earth twin system at 10 pc with an exact replica of the solar zodiacal cloud, the corresponding exozodi dust flux per spatial resolution element (PSF FWHM) is a few-hundred times brighter than the Earth at 10 μm,[62,63] and still ~3 times brighter than the Earth seen at quadrature in the visible.[64] A bright exozodi disk will contribute a higher background noise and require precise modeling for background subtraction. Realistic and optimized observing scenarios for exo-Earth direct imaging missions[65] estimate that a factor of 10 increase in exozodi density level, e.g., from solar level (1 zodi) to 10 times higher (10 zodis), reduces the exo-Earth yield of such missions by a factor of ~2. While manageable, this loss in sensitivity is still significant and knowing individual exozodi levels (directly measured in the visible) will improve survey efficiency for future telescopes. A potentially more problematic effect of bright exozodi emission is the creation of "clumps," regions of density enhancement trailing and leading the planet in its orbit, as predicted by disk-planet interaction models and actually observed in the solar system. For instance, simulations conducted for a 4 m telescope in the case of an Earth analog embedded in exozodi clouds of different brightnesses[66] predict that at a level of ~20 zodis, local heterogeneities in the disk could be brighter than the planet at V-band and constitute important sources of confusion and false positives. The exact location and strength of these clumps is expected to vary with planet mass, semi-major axis and outer dust characteristics, e.g., density and typical grain size.[67] The current conundrum of proto-planet imaging in complex proto-planetary disks, and corresponding—possible—false positives and subsequent controversies[68,69,70,71] is a cautionary tale for higher-contrast "clumpy exozodi + small planet" configurations. A better understanding of exozodi brightness level, convolved complex structures and how to disentangle them from point sources (e.g., via spectral or temporal properties) is crucial to the success of future exo-Earths direct imaging missions, as recognized early on (e.g., Refs. 62, 72).

<u>*Current state of the art and limitations.*</u> The statistical analysis of LBTI exozodi survey data, the most sensitive measurements to date, indicates that the median level of exozodi emission around sunlike stars is 4.5 + 7.3 – 1.5 zodis[73] and below 26 zodis[7] with 95% confidence.* The LBTI measurements are hence encouraging for future missions, and the derived upper limit is commensurate with the confusion threshold proposed by Defrère et al.[66] for a 4 m optical telescope. However, LBTI exozodi level estimates are fairly insensitive to the disk spatial structure within the LBTI 0.3" diffraction-limited photometric aperture, and remain limited to the mid-IR. *To accurately estimate the exozodi background faced by future optical missions and go beyond model-dependent wavelength extrapolations, high-contrast exozodi observations are required in the visible.*

6. Observational advances required and recommendations

In spite of significant efforts and instrumental progress over the last 15 years, exozodi detection limits remain far above solar dust density levels and their detailed radial/azimuthal structures remain largely unknown, even around the nearest main sequence stars. While debris disks can be revealed at a variety of wavelengths, temperate/cool planets and exozodi structures (≳200K) can only be simultaneously imaged at visible to mid-IR wavelengths. To constrain the low-flux end of the exozodi luminosity function to make further progress on the exozodi science questions, a further 10-100× gain in dynamic range is required from the visible to the mid-IR. For ground-based mid-IR interferometric observations using 8–10 m class telescopes equipped with state-of-the-art nulling systems, a factor of 3–5× further improvement is possible before the fundamental background shot noise limit is reached. Beyond this, substantial progress requires ground-based ELTs or space-based platforms. Additionally, basic exozodi dust properties (e.g., density profile and size distribution) cannot be derived from mid-IR measurements alone, as illustrated by the hot excess phenomenon discovered in the near-IR (Section 5). **The next breakthrough in understanding the origins of exozodi clouds and their connection to planet properties requires spatially resolved visible and near-IR observations (Table 1). Our main recommendation is therefore to foster new instrumentation developments for (i) high-contrast space-based imaging systems in the visible, and (ii) ground-based high-contrast near-IR interferometric systems, using separate telescopes and aperture masking on ELTs.** For instance, visible observations with ≳1 m space-based telescopes at contrast levels below $\sim10^{-7,-8}$ per spatial resolution element—as specified for the WFIRST CGI instrument[74]—would cross an important threshold in debris disks physics, detecting exozodi at low enough optical depths (≲10× solar) that their structure will be dominated by transport phenomena rather than collisions.[75] But in order to map the detailed radial and azimuthal distribution of exozodi structures around individual stars and directly explore the connection between dust structures and planets, larger space telescopes are required, with visible to near-IR detection capabilities at $\sim10^{-9,-10}$ contrast levels—consistent with, e.g., the HabEx and LUVOIR large strategic mission concepts.

Table 1: Summary of observational capabilities required to make significant progress on key exozodi science questions.

	Wavelength Range	Flux-Ratio Detection Limit (per resolution element)	Inner Working Angle	PSF FWHM (1)	Temporal Sampling
What is the Exozodi Luminosity Function?	Visible to mid-IR	$<10^{-7}$ at V band $< 10^{-4}$ at 10 µm	< 100 mas (1 AU at 10 pc)	N/A (2)	N/A
Can exozodi structures be used to infer the presence of exoplanets?	Visible to near-IR	$<10^{-9}$ at V band $<10^{-6}$ at 10 µm	<100 mas (1 AU at 10 pc)	<50 mas (0.5 AU at 10 pc)	Multiple epochs, months to years apart
What is the origin of the hot excess phenomenon?	Visible to 5 µm	$<10^{-3}$	< 5 mas (0.05 au at 10 pc)	N/A(**)	Multiple epochs, weeks to years apart
What is the impact of exozodi on the science yield of future missions?	Visible to mid-IR	$<10^{-7}$ at V band $<10^{-4}$ at 10 µm	< 100 mas (1 au at 10 pc)	<50 mas (0.5 AU at 10 pc)	Multiple epochs, months to years apart

(1): For an imaging system with many sub-apertures, e.g., multiple telescope aperture synthesis interferometry, the indicated PSF full width at half maximum (FWHM) reflects the synthetic PSF size rather than the diffraction limit of individual apertures. (2): Measuring total exozodi flux with high accuracy for faint dust levels still requires resolving the disk from the star, i.e., a small inner working angle.

* This number benefits from averaging over the full sample of 23 sunlike stars observed, and should not be confused with the 3σ detection limit *per individual star*: typically 60 zodis for early spectral types and ~150 zodis for solar analogs.

Acknowledgements

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1] Kelsall, T. et al. 1998, ApJ 508, 44
[2] Fixsen & Dwek 2002, ApJ 578, 1009
[3] Nesvorny D., et al. 2010, ApJ 713, 816
[4] Kral, Q., et al. 2017, AstRv 13, 69
[5] Lawler, S. et al. 2009, ApJ 705, 89
[6] Defrère, D. et al. 2015, ApJ 799, 42
[7] Ertel, S. et al, 2018, AJ 155, 194
[8] Kennedy, G. M. & Wyatt, M. C., 2013, MNRAS 433, 2334
[9] Wyatt, M. C. et al. 2005, A&A 433, 1007
[10] Kennedy, G. M. & Piette, A., 2015, MNRAS 449, 234
[11] Bonsor, A. et al. 2012, A&A 548, 104
[12] Wyatt, M. C. et al. 2007, ApJ 658, 569
[13] Bonsor, A. et al. 2018, MNRAS 480, 5560
[14] Weinberger, A. et al. 2011, ApJ 726, 72
[15] Lisse C. et al. 2007, ApJ 657, 584
[16] Absil et al. 2006, A&A, 452, 237
[17] Absil et al. 2013, A&A 487, 1041
[18] Akeson et al. 2009, ApJ 691, 1896
[19] Ertel, S. et al, 2014, A&A 570, 128
[20] Beichman, C. et al. 2006, ApJ 639, 1166
[21] Bryden, G. et al. 2006, ApJ 636, 1098
[22] Hinz, P. et al. 1998, Nature 395, 251
[23] Liu et al. 2009, ApJ 693, 1500
[24] Colavita, M. M. et al. 2009, PASP 121, 1120
[25] Serabyn, E. et al. 2012, ApJ 748, 55
[26] Millan-Gabet et al, R. 2011, ApJ 734, 67
[27] Mennesson, B. et al. 2014, ApJ 797, 119
[28] Hinz, P. et al. 2014, SPIE 9146
[29] Defrère, D. et al. 2016, ApJ 824, 66
[30] Hinz, P. et al. 2016, SPIE Conf. Proc 9907
[31] Weinberger, A. et al. 2015, ApJS 216, 24
[32] Schneider G. et al. 2014, AJ 14, 598
[33] Moro-Martin, A. et al. 2005, ApJ 621, 1079
[34] Raymond, S.N. et al. 2011, A&A 530, 62
[35] Burrows, C. 1995, AAS 187, 3205
[36] Mouillet, D. 1997, MNRAS 292, 896
[37] Lagrange, A. M. et al. 2009, A&A 493L, 21
[38] Bowler, B. P. 2016, PASP 128, 2001
[39] Meshkat, T. et al. 2017, AJ 154, 245
[40] Ruffio, J. B. et al. 2017, ApJ 842, 14
[41] Beuzit, J. L. et al. 2019, https://arxiv.org/abs/1902.04080
[42] Stone, J.M. et al., 2018, AJ, 156, 286S
[43] Di Folco et al. 2007, A&A 475, 243
[44] Defrère, D. et al. 2011, A&A 534, A5
[45] Mawet, D. et al. 2011, ApJ 738, 12
[46] Marshall, J.P. et al. 2016, ApJ 825,124
[47] Mennesson, B. et al. 2011, ApJ 736, 14
[48] Lebreton, J. et al. 2013, A&A 555, 146
[49] Kirchschlager, S. et al. 2017, MNRAS 467, 1614
[50] van Lieshout, R. et al. 2014, A&A 572, 76
[51] Czechowski & Mann 2010, ApJ 714, 89
[52] Su et al. 2013, ApJ 763, 118
[53] Rieke, G. et al. 2016, ApJ, 816, 50
[54] Kimura, H. et al. 2018, 2018arXiv180803389K
[55] Beust & Morbidelli 2000, Icarus 143, 170
[56] Thebault & Beust 2001, A&A 376, 621
[57] Gomes, R. et al. 2005, Nature 435, 346
[58] Bonsor, A. et al. 2014, MNRAS 441, 2380
[59] Faramaz, V. et al. 2017, MNRAS 465, 2352
[60] Ertel, S. et al. 2016, A&A 595, 44
[61] Nunez, P. et al. 2017, A&A 608, 113
[62] Mennesson, B. & Mariotti, J.M. 1997, Icarus, 128, 202
[63] Defrère, D. et al. 2010, A&A 509, 9
[64] Roberge, A. et al. 2012, PASP 124, 799
[65] Stark C. et al. 2015a, ApJ 808, 149
[66] Defrère, D. et al. 2012, SPIE 8442
[67] Stark, C. et al. 2011, AJ 142, 123
[68] Thalmann, C. et al. 2016, ApJ 828, L17
[69] Reggiani, M. et al. 2018, A7A 611, 74
[70] Mendigutia, I. et al. 2018, A&A 618, 9
[71] Sissa, E. et al. 2018, A7A 619, 60
[72] Beichman, C. & Velusamy, T. 1997, AAS meeting 191, 29, 1310
[73] Ertel et al. 2019, in preparation
[74] Mennesson, B. et al. 2018, NAS Exoplanet Science Strategy White paper
[75] Kuchner, M & Stark, C. 2010, AJ 140, 1007