arXiv:2110.04319v1 [astro-ph.EP] 8 Oct 2021

Debris Disks

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1 Introduction

Debris disk is a catch-all term that can be used to refer to any component of a planetary system which is not an actual planet. In the Solar System this refers to the asteroids and comets in the Asteroid and Kuiper belts as well as the dust and gas derived from them, such as the zodiacal cloud. Studying the structure of extrasolar debris disks provides unique constraints on the underlying planetary system and on the processes of planet formation and protoplanetary disk evolution. Debris disks also have important implications for processes affecting the planets, such as impact events that may strip an atmosphere or deliver volatiles. Their presence or absence also has consequences both positive and negative for the detectability of exoplanets in the system. Here I describe five of the most important ways in which debris disks will contribute to our understanding of extrasolar planetary systems in the coming years.

2 Placing the Solar system in context

Debris disks were first discovered over 30 years ago from the far-infrared emission of circumstellar dust heated by the star [7]. This continues to be the main method of discovery and several hundred such cold debris disks are known, with temperatures that place the dust at 10s of au from their stars (i.e., at distances comparable with our own Kuiper belt). Most recently *Spitzer* and *Herschel* surveys have quantified the incidence of detectable cold emission as $\sim 20\%$ across the spectral type range A-K [23, 93, 88] and has shown that such disks decay in brightness as the stars age [82, 99] in a manner that can be explained by mass loss due to collisional erosion within a population of planetesimal belts [104, 54, 30]. However, we are not yet able to detect true analogues to the Solar System's debris disk [9, 95]. Thus we cannot answer how typical the Solar System is in terms of its Kuiper belt and zodiacal dust levels (i.e., where it sits amongst the $\sim 80\%$ of stars without detectable debris). This is important to place our best example of a habitable planetary system into context, especially if debris played a role in its habitability and in the evolution of life [e.g., 1, 77, see also §4].

While *Herschel* had the sensitivity to achieve detections at a few times Solar system levels [23], such photometric surveys are fundamentally limited in that a Kuiper belt analogue emits less than 1% of the stellar flux at all wavelengths, whereas neither the stellar flux nor the instrumental calibration are known that accurately [e.g., 51]. Essentially this has limited our current knowledge to the brightest 20% of extrasolar Kuiper belts and the brightest $\sim 1\%$ of exozodiacal clouds [i.e., analogues to the cometary dust seen in the inner Solar system; 44]. To detect true Kuiper belt analogues, these would have to be resolved from the stellar emission, which requires high resolution imaging capabilities with well characterised instrumental systematics to reach the high contrast of the disk relative to the star, as well as techniques to mitigate background confusion at some wavelengths [e.g., in the far-IR where there is a high density of extragalactic sources, 74].

Recent improvements in nulling mid-IR interferometric techniques have resulted in detections of exozodiacal emission with *LBTI* at 30 times Solar system levels [25]. However, this still means that it is only the brightest $\sim 20\%$ of exozodi that have been detected, and inferences about lower dust levels have to be gleaned by extrapolation. Yet, such low levels are important not only for their astrophysical context (i.e.,

how the Solar system's cometary dust levels compare with other stars), but also because this dust is a serious hindrance in our ability to detect emission from exo-Earths and its presence or absence must be factored in to the design of telescopes such as *HabEx*, *LUVOIR* and *LIFE* [84, 80]. For now such extrapolations suggest that the median exozodi level could be as low as 3 times Solar system levels [25], which would be good news for exo-Earth detection. However, this remains to be confirmed with more sensitive observations and we can only confidently say this median is < 27 times Solar System levels.

Fortunately there is a range of instrumentation coming on-line that will help progress towards the detection of true analogues to the Solar system's debris disk, and so our understanding of the Solar system's place within the wider population. The *LBTI* techniques and instrumentation can be improved, and *JWST* provides high resolution and sensitivity mid-IR imaging that is imminent. Shortly thereafter, even higher resolution capabilities will become available with *ELT* and coronagraphic imaging with *WFIRST*. Further in the future far-IR observatories such as *Spica* and the *Origins Space Telescope*, if approved, would have the capability of detecting true Kuiper belt analogues towards the nearest stars [85]. In the meantime, studies of the brightest 20% of debris disks also provide a perspective on how the Solar system may have looked early in its history, before the system-wide instability that depleted the Kuiper belt [9, see also §3], or shortly after giant impact events like that which formed the Moon [39, see also §4].

3 Constraints on planetary system architecture and evolutionary history

The proximity of nearby stars (10s of pc) and the large size of most debris disks (typical radii in the range 30-150 au) means that, for the brightest disks their emission can be spatially resolved providing a map of the dust distribution in the system. Indeed the first debris disk was imaged around the star β Pictoris soon after its discovery [90], though it was not until 14 years later that the next five debris disk images were taken [36, 32, 41]. By now, well over 100 debris disks have been spatially resolved, at a range of wavelengths from the optical, at which starlight scattered by the dust is seen, and where the stellar emission has to be suppressed by coronagraphic techniques, to the sub-mm, at which thermal emission from mm- to cm-sized dust is seen that is thought to trace the parent planetesimals [for a review, see 38].

In general the structures observed in debris disks are well described as planetesimal belts. However, these *belts* range in width from narrow rings ($\Delta r/r \approx 0.1$) to broad disks ($\Delta r/r > 1$). Some of those which are broad have radial sub-structure such as gaps which may be carved by planets, [e.g., 59, 62, 63], reminiscent of similar structures seen in protoplanetary disks [3], albeit over a narrower range of radii. The inner edges of many disks are found to be sharp, which has been inferred to be evidence for sculpting by a planet at the inner edge [15]. However, there are other possible interpretations, such as the radial profile being set by where planetesimals were able to form within protoplanetary disks, such as at snowlines [e.g., 86]. Indeed there is emerging evidence that the radii of debris belts may correlate with snowline locations [66].

The vertical structure of disks that are not face-on can also now be resolved, with scale heights of order a few % being inferred and linked to stirring processes by bodies embedded within or near to the disks [17, 67]. Non-axisymmetric structures in the disks also provide evidence for planet-sized bodies, the most unambiguous of which is the warp in the β Pictoris disk, since that may be linked to the known planet in the system [50, 5]. Other asymmetric structures, such as eccentric disks, clumps and spirals [98, 43, 21], have also been interpreted as evidence for planets. However, more examples of systems where known planets can be linked to observed disk structures would boost confidence in what can be inferred from disk structures about underlying planetary systems. Nevertheless, we can be confident that even small planets (e.g., as small as Neptune or even Earth) would leave an imprint in the structure of a debris disk [e.g., 101, 79, 87], moreover one that would be readily detectable with current imaging capabilities. Thus high resolution observations of disk structure have the potential to pinpoint the location of planets that would otherwise be extremely hard to detect using any other techniques (e.g., Neptune analogues), and also can inform about their evolutionary history [e.g., providing evidence of past migration; 97].

We are truly in an era of high resolution disk imaging, with *ALMA* continuing to image new disks that can be followed up at even higher resolution. *JWST* looks set to provide further high resolution images both of exo-Kuiper belts and of any (mid-planetary system) dust structures that may lie inside these. Longer term, coronagraphic imaging with *WFIRST* and *ELT* will provide further advances. These disk images

provide our best window into outer planetary systems and the mechanisms involved in their formation and evolution. Theoretical modelling techniques will also continue to be developed to find ways to extract more concrete evidence for the presence of planets from the images, e.g., using kinematic structures in the gas [21, 92], and this field will further benefit when direct imaging capabilities allow the detection of planets toward more than a few % of stars.

4 Planetary bombardment

As noted in §2, there remains uncertainty about the level of cometary activity in the inner few au of nearby stars, as traced by their level of exozodiacal dust. However, it is already clear that for 20% of stars, the level of dust in their inner regions is orders of magnitude higher than in the Solar system. These exozodi detections correlate with the presence of an outer belt [71, 25], but it is debated whether this dust is dragged inwards from the outer belt [e.g., 83] or if the material arrives in the inner regions on larger planetesimals through scattering amongst a planetary system before being released by sublimation or disintegration [e.g., 22, 58]. It will soon be possible to test such models by using *JWST* (and later *WFIRST* and *ELT*) to search for dust at intermediate ~ 10 au separations. However, it is already evident that dust levels in some systems are too high to be explained by drag processes and so planetesimal delivery is required [20, 83].

If exozodis are replenished by planetesimals this opens up the possibility that some of these planetesimals may collide with planets in the system, an interaction with implications for conditions on the planets' surfaces. For example, planetesimal bombardment can both deplete a pre-existing atmosphere and deliver complex organic molecules and water, as well as volatiles that can be released to supply a secondary atmosphere [69, 16]. The level of planetesimal bombardment in a system depends on a number of factors, most of which are completely unknown, such as the architecture of the outer planetary system. While this means there is potential for constraining that planetary system from observations of exozodiacal dust and its relation to any outer belt [i.e., providing complementary information to that discussed in §3, e.g., 27, 100, 64], there are a number of theoretical hurdles. Notably, there is still not a complete model that links the level of zodiacal dust to its origin in comets [73]. Clearly there is scope for improved models that include all of the processes at play in debris disks, including dynamical interactions, collisions, radiation forces, gas release, gas drag, etc. [e.g., 46, 78].

While the exozodiacal dust observations show that it is plausible that planetesimal bombardment is ongoing in a significant fraction of systems, it should be acknowledged that bombardment does not need to be ongoing to have (or have had) a significant effect on a planet. High levels of warm dust are more common around stars in the first few 100 Myr of their lives [e.g., 89, 44], which could be indicative of an early bombardment phase as planetesimal belts are being cleared. Indeed, the Solar system's terrestrial planets are thought to have experienced high bombardment levels early in their history [72]. In general what matters for a planet is its integrated bombardment, the timing being less critical, and so it will be important to understand what these young bright warm disks tell us about typical bombardment histories.

This evidence for bombardment is opening up new lines of research, since it is now possible to consider for example how this would affect a planet's propensity for habitability. It has been shown that there is a shoreline in planet mass versus semi-major axis space that divides planets that would be expected to grow secondary atmospheres under bombardment, and those that would be expected to have their atmospheres eroded [102]. This process would be competing with the effects of evaporation due to irradiation by the star, but also with secondary outgassing as well as geological processes. Such interactions have been considered for Solar system bodies where the bombardment history is better constrained, but it is becoming relevant to consider such processes in an exoplanetary context, given the growing body of constraints on exoplanetary atmospheres and geology.

Whereas systems with bright hot dust were discussed above in the context of external bombardment onto the planets, it has also been interpreted as evidence for ongoing planet formation processes [105]. Specifically, this could be the dust created in the final giant impact stage of terrestrial planet growth. There is evidence for this in one system from the silica composition of its dust inferred from the infrared spectrum [52]. The rapid variability in some systems [70] is also explained in this context [40, 91]. If so, observations of these extreme debris disks tell us something about the timing and duration of the giant impact phase, and potentially about the frequency of terrestrial planet formation [e.g., 39]. For example, for Sun-like stars

this dust is seen within a few 0.1 au of the star, which could be because this is where planets tend to form for such stars. This is perhaps unsurprising given the prevalence of close-in super-Earth systems seen in transit surveys, but this could mean that Solar system-like configurations are rare. The coming years will see more examples of such extreme disks, as well as studies of their variability. We can also expect advances in the models for their interpretation which need to include a wider range of physical effects (e.g., due to the optical depth of the dust). There are also puzzles that for now defy easy explanation, such as the rapid dispersal of one disk [68], and the high fraction of stars with significant quantities of $\sim 1000\,\mathrm{K}$ dust [e.g., 24]. Solutions to these puzzles may come in the form of theoretical insights [e.g., 81, 78] or from further observational characterisation of the phenomena.

5 Planetesimal composition

A fundamental property of the circumstellar material is its composition. This could provide information on where and when the planetesimals replenishing debris disk dust formed, as well as how those bodies may have been subsequently altered by physical and geological processes.

The spectrum of the dust emission can in some cases be used to infer what it is made of. Spectral features in the mid-IR associated with silicates are often used in this way. However, most debris disks are too cold to emit in the mid-IR. Such spectral features are also sensitive to the size of the dust, being present only if the dust is smaller than the mid-IR wavelengths that characterise the feature. Nevertheless, this has been used to show that the bright warm dust in a few systems is silicate-rich and bears a similarity to dust compositions found in the Solar system [53], while in one case the abundance of silica implied formation in a recent giant impact [52]. *Herschel* opened up a new possibility for the colder disks which was to identify forsterite features at $69\,\mu$m, allowing the fraction of Fe and Mg to be determined [18]. However, this was only achieved for 2 disks. Future far-IR observatories like *Spica* could make such measurements routine. Scattered light observations also have the potential to probe the dust composition, e.g., through its colour or phase function [e.g., 19], although such inferences are again prone to sensitivity to the size of the dust and are limited by how well we can model dust optical properties. Nevertheless, those optical properties can be characterised using techniques like the discrete dipole approximation [e.g., 6], and empirical comparisons with Solar system objects are also possible [34]. The current set of observations with instruments like *GPI* and *SPHERE* have lead to a recent increase in the number of scattered light detections [75, 26], and these will gain momentum with *JWST*.

The volatile content of the planetesimals is harder to probe through spectral features, though there are mid- and far-IR features due to ice that could be detected by *JWST* and *Spica* [45]. However, *ALMA* is providing a growing body of observations of gas in debris disks which is thought to have a secondary origin, i.e., to have been released from volatile-rich planetesimals, rather than being a remnant of the protoplanetary disk [21, 61, 60]. Most commonly detected is CO, but there were a few detections of atomic carbon and oxygen with *Herschel* [e.g., 12], and neutral carbon detections with *ALMA* are becoming more prevalent [35, 13, 48, 14]. The paradigm within which these observations are interpreted is that of release of volatiles during the collisional cascade process, with those molecules photodissociating relatively quickly to produce an atomic gas disk that spreads viscously [47, 49]. The relative abundances of the observed gas and dust constrain their abundances on planetesimals which looks to be similar to Solar system comets [61, 65]. This paradigm is not without its challenges, for example there remains debate about whether the gas is produced stochastically rather than in steady state [13, 14]. We can expect significant observational progress on this in the coming years, first with *ALMA* and *SOFIA*, but in the future with *Spica*. These observational advances will have to go hand-in-hand with improvements in the models to accurately couple the hydrodynamical evolution of the gas with its thermodynamics and chemistry.

Perhaps the most direct measurement of planetesimal composition comes from observations of white dwarf atmospheres [e.g., 28]. These are frequently seen to be polluted with metals which have short sinking times, and so require constant replenishment which is inferred to be from planetesimals that are tidally disrupted before forming a disk that accretes onto the star [42, 37]. Multiple species have been observed in the atmospheres of many stars allowing the bulk composition of the pollutants to be measured, which can then be interpreted in terms of the temperature at which the planetesimal formed and the differentiation processes that it underwent since formation [8]. While such inferences are possible, there are still many unknowns; e.g.,

there is no direct evidence for the location of the parent planetesimal belt [29], the mechanism which caused the planetesimal to arrive at the star is not known, as are the details of the tidal disruption and disk accretion process [94]. With large numbers of white dwarfs being discovered in the era of large all-sky surveys like *Gaia*, *SDSS*, *ZTF* and *LSST* [31], and follow-up spectroscopy being performed to characterise any pollution, we can anticipate new observational results in the coming years, as well as significant theoretical progress on the various steps needed for the interpretation.

6 Protoplanetary disk dispersal

The recent far-IR surveys of *Spitzer* and *Herschel* have reinforced the paradigm in which stars are born with a planetesimal belt that subsequently erodes through collisional processing that passes mass from large planetesimals down to dust that is eventually expelled by radiation forces [104, 63]. This model fits the statistics for the fraction of stars seen to have detectable emission as a function of age in different wavebands. However, as already noted this necessarily cannot explain the 80% of stars without detectable disks. Further analysis of the current detections is also leading to new insights, such as a correlation of planetesimal belt radius with stellar mass [66]. The model also avoids the question of how and when the planetesimal belts formed, rather presupposing that these are present, with a collisional cascade already set up, as soon as the protoplanetary disk disperses. However, with the discovery of gas in debris disks, and the knowledge that dust in protoplanetary disks is not primordial but subject to a continual cycle of growth and destruction, it is becoming clear that the distinction between the two types of disk is not well defined [103]. This is particularly noticeable when considering the youngest systems, < 20 Myr or so, which means that observations of such young stars can inform on the processes of protoplanetary disk dispersal and of the birth of a debris disk.

Studies of young stars generally involve first identifying associations of stars that appear co-eval and with similar distances and space motions. However, the relevant kinematic information has until now not been available for the nearest star forming regions which lie at ~ 150 pc. While it has nevertheless been relatively unambiguous to identify protoplanetary disks in this way (i.e., the class II stars), this is harder for the young stars without such an obviously bright disk (i.e., the class III stars), with background stars often mistakenly falling in this category [57]. Gaia is changing that, and the coming years will see improved membership of the different nearby associations from which to study their disk populations [10, 56]. At the same time, *ALMA* observations of such regions have until now been relatively shallow, i.e., only sensitive to protoplanetary disks [e.g., 4, 96]. However, deeper *ALMA* observations can probe for dust emission at levels of the brightest debris disks in the nearest star forming regions, and can also search for remnant primordial gas that may have yet to disperse after the dust has been depleted [e.g., 76]. Thus it is timely now to perform a census of the youngest debris disks as well as to search for protoplanetary disks in the final stages of dissipation [e.g., 55]. Far-IR surveys are still more sensitive than those in the sub-mm, and for those we will have to wait for *Spica* which would be able to set limits on the presence of dust that are comparable with those for nearby stars (except where imaging has been able to probe fainter dust, see §2).

Significant advances have also been made in our understanding of protoplanetary disks, both in their observational characterisation and in theoretical advances in modelling the processes within them [for a recent review, see 2]. These will continue along with the advances in debris disks described in this chapter, and together it should be possible to infer the sequence of events that lead to the depletion of a protoplanetary disk. Observations of the gas will be particularly telling, since this component dominates the mass of a protoplanetary disk, and its dynamical influence is responsible for much of the dust morphology in such disks. Observations of the dispersal of that component in a disk wind would constrain that process [33], as well as its impact on dust and planetesimals in the disk [11, 76], and planet formation more generally.

7 Opportunities and challenges

Debris disks represent an opportunity, by providing unique information about exoplanetary systems. Observationally one challenge is to detect debris disks as faint as those in the Solar System, particularly given how relatively bright the host star is. Theoretically the challenge is to extract reliable information in the face of so many unknowns about the architecture, history and detailed physics of the underlying planetary system.

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