

Debris Disks: Probing Planet Formation

Mark C. Wyatt

Abstract Debris disks are the dust disks found around $\sim 20\%$ of nearby main sequence stars in far-IR surveys. They can be considered as descendants of protoplanetary disks or components of planetary systems, providing valuable information on circumstellar disk evolution and the outcome of planet formation. The debris disk population can be explained by the steady collisional erosion of planetesimal belts; population models constrain where (10-100 au) and in what quantity ($> 1M_{\oplus}$) planetesimals (> 10 km in size) typically form in protoplanetary disks. Gas is now seen long into the debris disk phase. Some of this is secondary implying planetesimals have a Solar System comet-like composition, but some systems may retain primordial gas. Ongoing planet formation processes are invoked for some debris disks, such as the continued growth of dwarf planets in an unstirred disk, or the growth of terrestrial planets through giant impacts. Planets imprint structure on debris disks in many ways; images of gaps, clumps, warps, eccentricities and other disk asymmetries, are readily explained by planets at $\gg 5$ au. Hot dust in the region planets are commonly found (< 5 au) is seen for a growing number of stars. This dust usually originates in an outer belt (e.g., from exocomets), although an asteroid belt or recent collision is sometimes inferred.

Introduction

Many 100s of debris disks are now known, most of which were discovered in far-IR surveys of nearby stars implying the presence of cold dust. The ubiquity of debris disks is apparent from the fact that such circumstellar dust is present at a detectable level around $\sim 20\%$ of nearby main sequence stars. The dust is thought to have a much shorter lifetime than the stellar age, implying that this is not primordial (i.e.,

Mark C. Wyatt
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom, e-mail: wyatt@ast.cam.ac.uk

not left over from the protoplanetary disk phase). Rather the dust is inferred to be secondary, continually replenished from the break-up of larger planetesimals.

The proximity to the Sun of many debris disks means the structure of this cold dust can be studied at high resolution. Such imaging has shown that the dust is often confined to a ring-like geometry at 10s of au. Thus it is tempting to interpret debris disks as extrasolar analogues to the Kuiper belt. A smaller fraction of stars show evidence in mid-IR observations for warm dust at a few au, which may be analogous to the Solar System's zodiacal cloud. Implicit in these analogies is the existence of a putative planetary system in the regions absent of dust. However, for most stars there is no strong evidence for the presence of any planets, and it remains possible that the parent planetesimals reside in otherwise empty systems. Nevertheless, given the ubiquity of extrasolar planets, and the growing number of systems with both debris and planets, it is plausible that **a debris disk is just one component of an underlying planetary system.**

This view of planetary systems as emerging fully formed from the protoplanetary disk phase shows that **observations of the debris disk component provide valuable information on the outcome of planet and planetesimal formation processes.** The presence of dust indicates where planetesimals either formed or ended up, and the detailed structure of the disks give clues to where there may be planets. However, again taking the example of the Solar System, it is also clear that planetary systems do not necessarily remain static after protoplanetary disk dispersal. The Earth's moon is thought to have formed in a giant impact at 50-100 Myr, and a dynamical instability involving the giant planets is thought to have lead to a restructuring of the planetary system architecture and depletion of the Kuiper and Asteroid belts possibly as late as 700 Myr after the formation of the Solar System. Both of these events would have been accompanied by a significant change in the observable properties of the Solar System's debris disk. Thus **debris disks can also provide evidence of ongoing planet formation processes.**

While the dust seen in debris disks may not be primordial, it is nevertheless still helpful to consider that **debris disks are the descendants of protoplanetary disks, informing on the processes of protoplanetary disk dispersal.** This is true for the dust because the solid material seen in the earlier phases must go somewhere, and there may be planetesimals present already within the protoplanetary disk. This view is also particularly relevant when considering the gaseous component of debris disks, evidence for which is accumulating for many stars, some of which are inferred to be have a component of primordial gas.

Debris disks as descendants of protoplanetary disks

In contrast to protoplanetary disks, which are optically thick at optical and infrared wavelengths and have large masses in mm-sized dust ($> 1M_{\oplus}$) and even more mass in gas, debris disks are optically thin with low mm-sized dust masses ($< 0.1M_{\oplus}$) and very little if any evidence for gas (see Fig. 1). However, the boundary between

the two types of disk is not well defined, and there are several examples of disks with different classifications depending on the criteria used (e.g., Schneider et al. 2013; Kennedy and Wyatt 2014). Part of the problem arises because it is not possible to detect analogues to the brightest debris disks (that are within a few 10s of pc) in nearby star forming regions that are beyond 100 pc (e.g., Hardy et al. 2015); e.g., stars in such regions that do not show evidence of $24\ \mu\text{m}$ emission above photospheric levels are designated as class III stars (as opposed to class I or II stars for which excess $24\ \mu\text{m}$ emission is present), and are normally considered diskless, even though these could harbor debris disks for which the dust emission simply lies below the detection threshold (e.g., Cieza et al. 2013). Thus it has been challenging to piece together the mechanism of protoplanetary disk dispersal and the subsequent (or concurrent, or indeed prior) birth of a debris disk.

Wyatt et al. (2015) outlined 5 steps in the transition from protoplanetary to debris disk. The first of these is the carving of an inner hole resulting in a morphology known as a transition disk, which may be evident from a disk image by an absence of dust emission in the regions close to the star, or from an absence of hot dust in the emission spectrum. However, it should be noted that it remains debated whether this transition disk morphology is a necessary step in the transition or just a different class of protoplanetary disk. The remaining 4 steps involve the removal of cold mm-sized dust from the outer 10s of au, the emptying of dust from the inner regions, the dispersal of the gas disk, and the shepherding of planetesimals into ring-like structures. It was acknowledged that the order of these steps is unknown and may vary between systems. It was also concluded that a defining feature of protoplanetary disks is the presence of gas in sufficient quantities to affect the dynamical evolution of the dust, and it is the gaseous component that will be the focus of this section.

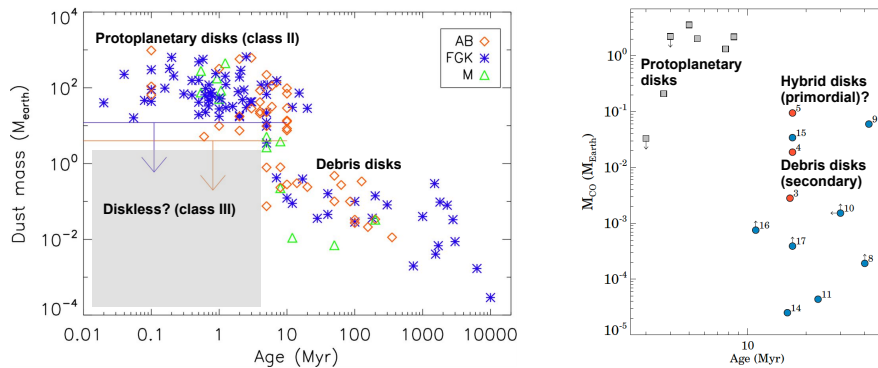


Fig. 1 Evolution of circumstellar disk mass, as determined from observations of sub-mm dust (left, Panić et al. 2013) and CO gas (right, Moór et al. 2017). Debris disks and protoplanetary disks are readily distinguished by the difference in disk mass and age on both plots. Horizontal lines on the left plot show the approximate pre-ALMA detection threshold in nearby star forming regions, which was insufficient to detect debris disk levels of dust around class III stars. Debris disk gas is likely to be secondary, although large CO gas masses around some young stars could indicate a primordial component, earning such disks the name *hybrid* disks.

Debris disk gas

The last few years have seen significant progress in our understanding of the evolution of circumstellar gas between the phases. Most importantly it is now clear that a gaseous component is present long into the debris disk phase for many systems. For example, whereas in the pre-ALMA era absorption by circumstellar gas along the line of sight was seen to two stars with edge-on debris disks, thanks to ALMA we now know that detectable levels of CO gas emission are present around roughly half (11/17) of 10-40 Myr-old A stars within 150 pc that have debris disks with fractional luminosities in the range 0.05-1% (Lieman-Sifry et al. 2016; Greaves et al. 2016; Moór et al. 2017); here fractional luminosity is defined as the ratio of the luminosity of the dust emission to that of the star. Gas mass estimates contain many uncertainties, but the strength of the CO lines is diminished for debris disks compared with protoplanetary disks (e.g., Péricaud et al. 2017), although for some debris disk systems the inferred disk mass may be comparable (see Fig. 1). For now it is young A stars that dominate the samples of debris disk gas detections (Lieman-Sifry et al. 2016), but gas is also seen around both later F-type stars (Marino et al. 2016, 2017b) and older stars up to 1 Gyr (Matrà et al. 2017b; Marino et al. 2017b).

Secondary origin of debris disk gas

While the ubiquity of circumstellar gas is becoming clear, its origin remains unknown for most systems. The gas could be either primordial (i.e., a remnant of the protoplanetary disk) or secondary (i.e., the volatiles are locked in icy planetesimals until released in collisions). Differentiating between these possibilities is difficult because (similar to protoplanetary disks) it is still hard to detect anything but CO. Nevertheless, for some systems an unambiguous origin for the gas can be ascertained. For example, for β Pictoris the striking similarity of the morphology of the CO gas disk and that of the dust disk, both of which are distributed over 60-130 au and include a prominent clump, argues for a secondary origin (Dent et al. 2014). This is supported by the CO line ratios that rule out a primordial abundance of hydrogen which if present would lead to LTE line ratios that can be ruled out (Matrà et al. 2017a).

That we can detect CO at all in β Pictoris is inferred to arise from a high CO production rate of $0.1M_{\oplus}/\text{Myr}$, since photodissociation by interstellar radiation occurs on 120 yr timescales. It is hard to get around this short CO lifetime, even with CO self-shielding, and is the likely explanation for the small numbers of CO detections around other debris disks until now. The dust production rate is also high in this disk, and assuming that gas and dust are lost in proportion to their composition, an up to 6% by mass ratio of CO is inferred consistent with Solar System comets (Matrà et al. 2017a). This picture of steady state replenishment of the gas is reinforced by the detection of the atomic C disk by far-IR spectroscopy of the CII line at levels compatible with this scenario if the atomic gas spreads viscously (Kral et al. 2016). This is also compatible with observations of OI (Brandeker et al. 2016), par-

ticularly if the planetesimal composition includes H₂O in similar quantities to Solar System comets (Kral et al. 2016). The situation is similar in several other debris disks with CO gas detections; e.g., 23 Myr HD181327 and 400 Myr Fomalhaut both have CO coincident with their much narrower dust rings at levels compatible with steady state production from comets with of order 10% volatile fraction (Marino et al. 2016; Matrà et al. 2017b). In fact, applying this logic to all known dusty debris disks shows that it is plausible that all of these have comet-like compositions and hence also have CO, CII, OI and CI present at some level, with only the brightest systems detected thus far (Kral et al. 2017).

Primordial debris disk gas: hybrid disks?

The success of a secondary explanation for the β Pictoris gas disk is in contrast to its failure to explain the gas seen toward HD21997 (Kóspál et al. 2013). The CO gas orbiting this 30 Myr A3V star is found at radial locations (from < 26 au to 138 au) where there are no mm-sized dust grains (which are found from 55 to > 150 au and thought to trace the location of planetesimals). The short gas lifetime requires the two to be co-located in the secondary scenario, leading to the suggestion that the gas is primordial, or that this is a *hybrid* disk where the gas has both origins. However, a short CO lifetime is equally problematic for the primordial scenario, unless the protoplanetary disk has dispersed implausibly recently. This suggests that the CO is shielded somehow to prevent its photodissociation. While the ¹²CO is optically thick, self-shielding cannot raise the CO lifetime to the ~ 1 Myr required for this to be a viable solution. Moreover, since photodissociation is driven by the interstellar radiation field, the problem cannot be circumvented by devising a thin disk geometry to prevent penetration of the stellar radiation. The solution may be to invoke an unseen gaseous component, such as hydrogen which would be abundant if the gas is primordial. However, the resulting collisions would imply that the 5.6 K excitation temperature inferred from CO line ratios is the kinetic temperature of the disk (i.e., that the disk is in LTE), which is significantly lower than that expected from protoplanetary disk observations. Hughes et al. (2017) reached a similar conclusion for the 49 Ceti gas disk, that the temperature and gas scale height require a relatively high mean molecular weight, disfavoring a primordial origin for the gas in this disk.

Thus HD21997 presents a puzzle, and similar considerations apply to other young A stars with bright debris disks and significant levels of CO gas emission (e.g., Péricaud et al. 2017). Nevertheless, it is worth noting that while roughly half of young A stars with bright debris disks have gas, it is only $\sim 10\%$ of young A stars that have bright debris disks (Carpenter et al. 2009), which means that not all A stars necessarily go through this phase. Moreover, there is no evidence yet that this is not a phenomenon unique to A stars; e.g., Kral et al. (2017) devised a simple prescription to predict the expected level of secondary CO, and so quantify whether any of the current debris disk gas detections look anomalous, only identifying two further A stars HD131835 and HD138813 (also implying that most of the detections

in Fig. 1 could be consistent with secondary gas production). On the other hand, the persistence of primordial gas in some systems needs to be understood, since this could apply to other systems albeit at lower gas levels.

Implications of debris disk gas

Within the context of this review, a few things can be concluded. **(i)** The dispersal of primordial gas may be inefficient and leave significant quantities for 10s of Myr. This leaves open the possibility that gas is present that can be accreted onto planetary cores and so lead to continued growth of planetary atmospheres. If sufficient gas is present, this can also affect the dynamical evolution of the planetary system, for example damping planetary eccentricities and inclinations and leading to planet migration (see chapter by Morbidelli). Even moderate quantities of gas can affect the evolution of small dust grains, which could affect the interpretation of the observed dust properties (e.g., Takeuchi and Artymowicz 2001; Lyra and Kuchner 2013). For example, the presence of gas may prevent the removal of micron-sized dust that would otherwise be expelled by radiation pressure, thus explaining the anomalously high dust temperature (given its radial location) for some hybrid disks (Lieman-Sifry et al. 2016; Moór et al. 2017). **(ii)** Some fraction of the CO that is present in protoplanetary disks ends up in planetesimals later to be released. It is unclear whether the quantity that is sequestered from the disk is sufficient to affect the observed chemical structure of protoplanetary disks (see chapter by Bergin et al.). Nevertheless, secondary debris disk gas may be observational evidence for a process that started in the protoplanetary disk, thus allowing the two evolutionary phases to be connected. Moreover, debris disk gas observations already provide evidence for the volatile-rich composition of extrasolar planetesimals in some systems. This allows consideration of whether such volatiles can later be delivered to planets in the inner regions of the system, thus aiding conditions conducive to the development of life. The detailed composition of debris disk gas, e.g. from the detection of other molecular tracers like CN (e.g., Matrà et al. 2018), would also inform on processes in the protoplanetary disk such as condensation sequences (see chapter by Pudritz et al.).

Probing the outcome of planetesimal formation

Our understanding of dust evolution in protoplanetary disks has recently undergone significant advances (see chapter by Andrews & Birnstiel). For example, observations with ALMA provide observational evidence for dust growth and drift in broad agreement with theoretical expectations for its interaction with the gas disk, at least once the gas disk is allowed to have complex structure. However, there is as yet no observational evidence that planetesimals are present during the protoplanetary disk phase. Indeed such evidence would be hard to come by, because observations

are only sensitive to dust smaller than ~ 1 cm in size. Planetesimals (i.e., > 1 km objects) may be present, but their low opacity means that for realistic masses these would have no observable signature. While these same planetesimals may collide and produce dust that can have an observable signature, given the possible presence of gas to entrain the dust and the young age of systems with protoplanetary disks (up to a few Myr), it would be very hard to argue that the dust could not be primordial.

Baseline model of debris disks: planetesimal belt

This same argument does not apply to dust seen in the debris disks around > 10 Myr main sequence stars, for which the short lifetime of the observed dust is used to infer that larger planetesimals must be present. Such large bodies can survive over the age of the star in the face of collisions and radiation forces, providing a source population that continually replenishes the observed dust. This picture of debris disk dust being replenished in a steady state manner from collisions amongst belts of planetesimals has gained widespread support due to: images showing that mm-sized grains in many systems are confined to narrow rings (e.g., see Fig. 4, Marino et al. 2016; MacGregor et al. 2017), the inferred size distribution of mm-sized grains fitting with expectations of a collisional cascade (MacGregor et al. 2016), the presence of a halo of micron-sized grains outside these rings as expected due to radiation pressure (Strubbe and Chiang 2006), the size distribution of small dust close to the radiation pressure blow-out limit agreeing broadly with expectations (Pawellek et al. 2014), the manner in which disks are fainter around older stars being consistent with their depletion in collisional erosion assuming the presence of planetesimals at least a few km in size (Wyatt et al. 2007c; Löhne et al. 2008; Gáspár et al. 2013).

This means that debris disks provide valuable information on the outcome of planetesimal formation processes, showing where such planetesimals formed (or rather where they ended up), the size of those planetesimals, the total mass contained in the belts, and the level of stirring (i.e., collision velocities between planetesimals). However, it is often the case that this information is not uniquely constrained even for well studied disks. For example, for Fomalhaut for which imaging finds a belt radius of ~ 130 au and constrains the level of stirring (see chapter by Kalas), it is only possible to say that given its 440 Myr age, the planetesimals must be larger than a few km in size requiring a total mass of at least 10s of M_{\oplus} (Wyatt and Dent 2002). For most systems however, the radial location of planetesimals is much less well constrained and must be estimated from the dust temperature, and conclusions are degenerate with assumptions about the stirring level (and about planetesimal strength). Nevertheless, planetesimal sizes of 10s of km and disk masses of $> 1M_{\oplus}$ are the right ballpark for debris disks that can be detected.

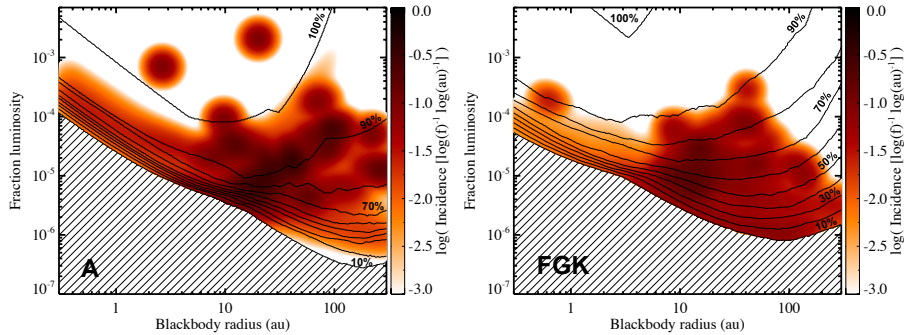


Fig. 2 Fraction of stars with debris disks of given fractional luminosity and black body radius, for the nearest 100 A stars (left) and the nearest 300 FGK stars (right) (using the samples in Phillips et al. 2010). The true disk radius is likely to be a factor of a few larger than the black body radius because the small grains that dominate the emission have relatively high temperatures due to their inefficient emission (Booth et al. 2013). The contours show the fraction of stars in these samples for which disks could be detected, going from 10% to 100% in 10% increments. This detection bias has been corrected for and disk incidence only plotted in regions where disks could be detected for $> 10\%$ of the stars, the remaining area being shown with cross-hatching. (Figure made by G. Kennedy using the technique described in Sibthorpe et al.).

Population model fits to debris disk statistics

Population models (e.g., Wyatt et al. 2007c; Löhne et al. 2008; Gáspár et al. 2013; Krivov et al. 2018) make the assumption that all disks have the same level of stirring, planetesimal strength and maximum planetesimal size, and use that to derive the underlying distribution of disk radii and initial masses, since that then sets the observable properties of disks expected to be found around a star of given age and spectral type which can be compared with observations. Fig. 2 summarises our current understanding of the observed disk properties, with the colour scale showing the fraction of stars that have a disk of given fractional luminosity and radius for the ~ 300 nearest FGK stars (left) and ~ 100 nearest A stars (right). These plots combine information from sufficient disks that the distributions are relatively smooth, although the blobs in the sparsely populated region of high fractional luminosity disks result from individual disks. For both spectral types, approximately 20% of stars have detectable disks (Eiroa et al. 2013; Thureau et al. 2014; ?), and with no far-IR space mission imminent, the complement of (cold) debris disks around nearby stars is unlikely to increase significantly any time soon. There are several well understood biases in detectability in this figure, which are explained in Wyatt (2008), but their implications can be understood from the contours on Fig. 2 which show the fraction of stars in the sample for which the observations would have been able to detect a disk in this part of parameter space (e.g., we cannot know what fraction of stars have disks that lie in the cross-hatched region).

The populations for both spectral type groupings are similar, in that they show disks concentrated at radii from 10-100 au, with fractional luminosities $10^{-6} - 10^{-4}$.

They also both exhibit an upside-down V-shape for the upper envelope where disks are found in Fig. 2. This shape is in good agreement with the predictions of steady state collisional population models. In such models the small radius side of this upper envelope (< 30 au) is caused by collisional depletion over the stellar age, since steady state collisional erosion is predicted to cause disks of the same radius to have evolved by a given age to the same mass and luminosity that is independent of their initial mass (a disk that is initially more massive will start out brighter but decay faster than one that is less massive, to end up at the same level). Since the disks included in Fig. 2 should all have suffered approximately Gyr of evolution, all close-in disks should lie below the same envelope, and any that have dust luminosities that lie significantly above this are inferred to be a transient phenomenon, since they cannot be explained by steady state processes (Wyatt et al. 2007b), unless they are found around young ($\ll 100$ Myr) stars. The large radius side of the upper envelope in the population models is set by the maximum initial mass present in the belts, and so such large disks ($\gg 30$ au) are inferred to have yet to undergo significant collisional depletion (due to the long collision timescales at this distance, see discussion in Wyatt et al. 2007c). For now, such population models have been used to show that steady state collisional erosion can explain most of the observed trends for A stars (Wyatt et al. 2007c), FGK stars (Löhne et al. 2008; Kains et al. 2011) and M stars (Morey and Lestrade 2014) (see also Gáspár et al. 2013), and thus also provide a plausible population from which to consider the detectability of such disks. However, it should be noted that any conclusions about the debris disks of the 80% of stars without detected disks rely on extrapolations from the known disks and include assumptions about the form of the underlying mass and radius distributions of the planetesimal belts. Ultimately though, it will be possible to use these population models to set constraints on the distribution of planetesimal belt masses and radii that emerge from the protoplanetary disk phase.

Comparing the observed distributions around A and FGK stars in Fig. 2, it is evident that the peak in the upside-down V (of the upper envelope of the dense coloured region where most disks are found) is at larger black body radius for the more massive stars. This implies that collisional erosion has progressed to larger distances around A stars, despite these stars being on average younger than the FGK stars. This could mean that collisional evolution is faster around the earlier spectral types, perhaps because the mass in their disks is dominated by smaller planetesimals. However, such an inference is complicated by the fact that the population of FGKs stars would be expected to shift further to the right if plotted against the true disk radius (rather than that inferred from the dust temperature assuming black body grains). Nevertheless, it seems that the debris disks of A stars and FGK stars do have some intrinsic differences (although the exact spectral type boundary at which any difference occurs is poorly constrained); e.g., it has also been suggested that A star disks tend to be more massive than those of FGK stars (Greaves and Wyatt 2003).

Beyond the baseline model

Detailed observations of individual disks also show ways in which the population models can be improved. For example, not all disks have planetesimals concentrated in narrow rings. Several are shown to be radially very broad (Booth et al. 2013), extending over a factor of 2 or more in radius. Collisional evolution of such disks can lead to a flat surface brightness profile (Schüppler et al. 2016) which can be very difficult to resolve in the sub-mm even when the disk is bright in the far-IR (Marino et al. 2017a). Other disks have been found to have dust concentrated at multiple radial locations. This was first inferred from the infrared spectrum which implied two temperature components were needed to fit the spectrum (Chen et al. 2014, see e.g. Fig. 3 right), requiring hot dust significantly closer to these stars than their cold outer belts (Su et al. 2013; Kennedy and Wyatt 2014). There are also examples of disks for which high resolution imaging has shown a broad outer belt to be comprised of two rings with a gap inbetween (see Fig. 3 left, Ricci et al. 2015; Golimowski et al. 2011), or in which a narrow ring has been found to have a fainter ring just outside (Marino et al. 2016). Such multiple components would be very hard to discern from the spectrum, and could indicate locations of preferential planetesimal formation (e.g., related to the ring-like structures seen in protoplanetary disks, see chapter by Andrews & Birnstiel), or provide evidence for sculpting by planets (see later discussion).

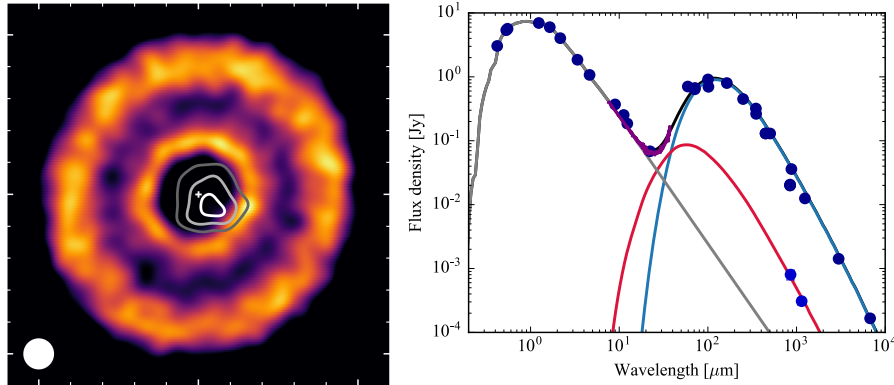


Fig. 3 Observations of the debris disk of the 80-200 Myr G2V star HD107146 (Marino et al., in prep.). (Left) ALMA images of the dust emission show that the broad (30-150 au) cold debris disk is resolved into two rings with a partially filled gap centred at 80 au. Emission from an additional warm dust component at 10 au is also evident in the residual contours (the emission remaining after subtraction of a model for the cold component). This warm component is also seen as excess mid-infrared emission in the spectral energy distribution of the star (right), which requires a warm temperature component (red) in addition to the emission from the star (grey) and the cold component (blue).

High resolution imaging also allows the level of stirring in the belt to be estimated. For example, through the scale height of edge-on disks (which gives direct

information on dust particle inclinations), or through the detailed structure of the halo of small dust extending beyond the ring (since small halo dust would be underabundant in a disk with low stirring as it is radiation forces not stirring that sets its depletion rate, Thébault and Wu 2008). While for most debris disks the origin and level of stirring is unknown, it may be notable that some disks have been inferred to have very low levels of stirring (eccentricities $< 1\%$), below which collisional depletion of the belts becomes very slow and the collisional production of small grains is prohibited rendering such disks relatively hard to detect (Krijt and Kama 2014). Indeed, the existence of unstirred disks (eccentricities $\ll 1\%$) of 10-100 m planetesimals that can survive Gyr of evolution has been proposed to explain the detection of faint anomalously cold debris disks with Herschel (Krivov et al. 2013), and so it may be that many unstirred debris disks lurk below the detection threshold on Fig. 2 (Heng and Tremaine 2010). That the absence of detectable emission does not necessarily indicate an absence of planetesimals should be evident from the fact that the Solar System's Kuiper belt would not have been detected in any of the current far-IR surveys of nearby stars (Vitense et al. 2012).

Given the difficulty of detecting planetesimals in protoplanetary disks mentioned above, there is for now very little information about when planetesimals formed. It is generally assumed that planetesimals form relatively early on ($\ll 1$ Myr) so that they can provide the building blocks for planets that are also thought to form before the protoplanetary disk disperses. Evidence from the Solar System also supports an early formation epoch for the asteroids (Wadhwa et al. 2007). However, it is typically the case that $> 1M_{\oplus}$ of dust is present in protoplanetary disks up to the epoch of its dispersal (see Fig. 1), leading to the possibility that at least one population of planetesimals could form during disk dispersal (e.g., Carrera et al. 2017; Ercolano et al. 2017). Observations of very young populations of debris disks (such as those around the class III stars found in star forming regions, see Fig. 1) will help to disentangle these early phases.

Debris disks as a component of a planetary system

While debris disks provide evidence for the successful formation of planetesimals in the outer regions (typically 10s of au) of many (at least 20%) protoplanetary disks, this does not automatically indicate that planets also formed in these systems. Similarity of the observed disks to the Solar System's Kuiper belt (Currie et al. 2015; Booth et al. 2017) provides circumstantial support for the presence of a planetary system, but hard evidence is needed to support this anthropocentric view. Such evidence can be found for the population as a whole by comparing samples of stars with debris disks and/or exoplanets, and for some individual systems from the detailed structure of their disks.

Correlations of debris disks and exoplanets

Evidence for a difference between the far-IR properties of the debris disks around stars with and without planets was lacking from studies of Spitzer data (Bryden et al. 2009), but has now been found following more recent surveys with Herschel that were both more sensitive and covered a larger number of exoplanet host stars (see Matthews et al. 2014). The disks appear to be on average slightly brighter when radial velocity planets are present. There is also evidence for a dependence on planet mass, in that systems with planets but where none is more massive than Saturn tend to have a higher incidence of detectable debris (Wyatt et al. 2012). However, such correlations remain tentative (Moro-Martín et al. 2015). At such vastly different spatial scales the planets ($\ll 5$ au) are unlikely to have any direct influence on the disk ($\gg 20$ au) detectability. Thus, if confirmed, these correlations could either point to the planets having an indirect influence on the outer planetesimals (e.g., because systems of high mass planetary systems scatter smaller planets out that can deplete an outer disk, Raymond et al. 2011), or to the outcome of planetesimal and planet formation at the different locations being linked through initial protoplanetary disk properties. For example, the increased debris disk brightness for the planet-host stars is at a level compatible with that expected if such systems formed from protoplanetary disks that are amongst the top 6% of the population in terms of their solid disk masses (Wyatt et al. 2007a), which is supported by the planet-metallicity correlation (Fischer and Valenti 2005) and possibly also by a correlation of debris disk mass with metallicity (Gáspár et al. 2016). Identifying a correlation of debris disks with planets imaged in the outer regions of the systems would be particularly informative, and it is notable that all currently known imaged planets are in systems with debris disks (Bowler 2016).

Structures associated with planets

Disk structure can be a very sensitive tracer of planets because the orbital motion of planetesimals is inevitably perturbed by the presence of planets. The same is true in protoplanetary disks, but the presence of significant quantities of gas makes linking observed dust structures to planets more complicated (see chapter by Andrews & Birnstiel). There is also complexity when interpreting debris disk dust observations, since the dust is affected by radiation forces. However, the way collisions and radiation forces cause the radial distribution of dust to differ from that of the planetesimals is reasonably well understood (Krivov et al. 2006), and through a range of modelling efforts it is also possible to understand how the two distributions are related even in more complex dynamical situations resulting in non-axisymmetric structure (Wyatt 2006). Thus interpretation of debris disk structures starts with consideration of how planetesimal orbits are affected by a planet's gravity. Such perturbations come in three types: secular, resonant and scattering.

Secular structures

Secular perturbations are long range interactions and allow a planet to modify the orbit of planetesimals even at large distance. For planets on relatively low eccentricity orbits ($e \ll 0.3$), such perturbations cause planetesimal orbits to become eccentric, with pericentres that precess at rates that depend on location in the disk. This can cause initially coplanar circular planetesimal orbits to cross, resulting in collisional destruction (Mustill and Wyatt 2009), and setting up a tightly wound spiral wave that propagates through the disk (Wyatt 2005a), eventually causing a disk to become eccentric (Wyatt et al. 1999). If the planet is inclined to the disk, the planetesimals' orbital planes also precess, again at a rate dependent on location, which can cause the disk to appear warped when viewed edge-on (Augereau et al. 2001). The secular perturbations of a highly eccentric planet, such as one scattered out by an inner planetary system, can cause bell-shaped structures, disks that are orthogonal to the planet's orbit, and double-ringed structures (Pearce and Wyatt 2014, 2015).

While most of these predicted features have been observed in debris disk images, the strongest evidence that these originate in planetary perturbations comes from a warp in the β Pictoris disk, for which the warp was used to predict the existence of a $9M_{\text{jup}}$ planet at 9 au that was later discovered by direct imaging (Lagrange et al. 2010). On the other hand, the structures associated with eccentric debris rings seem to be ubiquitous, possibly explaining large scale asymmetric features of scattered light images (such as those called *needles* and *moths*, Lee and Chiang 2016; Löhne et al. 2017), as well as a brightness asymmetry in the infrared that undergoes a 180° phase shift depending on wavelength (i.e., switching from *pericentre glow* to *apocentre glow*, Pan et al. 2016). The lack of eccentricity of a debris ring also limits the eccentricity of any orbiting companions (see Fig. 4, Marino et al. 2017b). The best characterised eccentric debris ring is that of Fomalhaut (see chapter by Kalas, Kalas et al. 2013; MacGregor et al. 2017), but the way in which this informs on the underlying planetary system is complicated by the discovery of a planet-like object Fomalhaut-b which orbits near the belt but cannot be responsible for the ring eccentricity (Tamayo 2014; Beust et al. 2014). It should be noted that the long range nature of secular perturbations means that perturbing objects could be either interior or exterior to the debris belt (Nesvold et al. 2017), and indeed it is suggested that the eccentricity in this system could arise from external perturbations from the companion stars (Shannon et al. 2014; Kaib et al. 2017).

Resonances: gaps, clearing and clumps

A planet's resonant perturbations only apply to planetesimals with orbital periods within narrow ranges. Nevertheless, resonant planetesimals can be overabundant due to resonant trapping during planet migration. The geometry of resonant orbits makes the distribution of planetesimals clumpy, allowing observed structures to reveal the mass, current location and past migration history of the perturbing planet (Wyatt 2003). The best evidence for resonant structures in debris disks is the clump

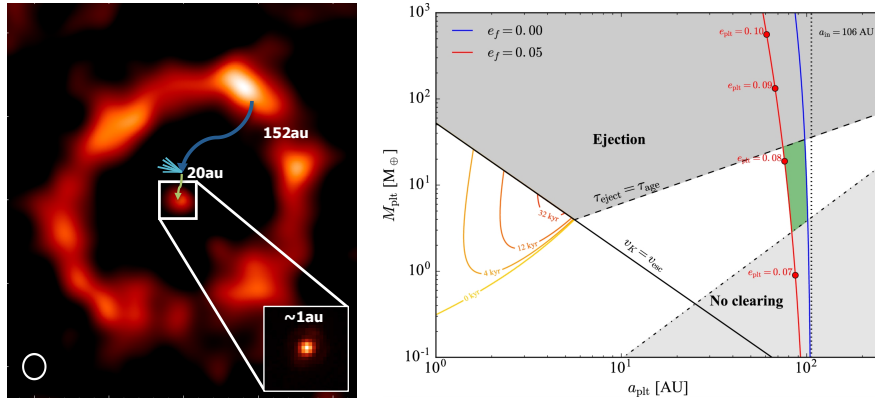


Fig. 4 Observations of the debris disk of the 1Gyr F2V star η Corvi (left) and implications for its underlying planetary system (right, Marino et al. 2017b). The debris disk has three components: a cold outer belt at 152 au imaged with ALMA (main image), CO gas at ~ 20 au thought to originate in icy planetesimals sublimating as they are scattered into the inner system (cartoon depiction), and an inner hot component at ~ 1 au possibly the refractory component of those planetesimals or the product of a collision with a planet (inset image Smith et al. 2008). If there is a planet sculpting the disk’s inner edge this must lie in the green shaded region with limited eccentricity due to the circular appearance of the disk. Inward scattering of planetesimals is inhibited if any planets lie in the *ejection* region (Wyatt et al. 2017). The yellow and orange lines show how long collisional debris from such planets would remain detectable.

in the β Pictoris disk (Telesco et al. 2005; Dent et al. 2014; Matrà et al. 2017a), with tentative signs in other disks (Hughes et al. 2012; Booth et al. 2017).

Planetary resonances also cause the region near a planet to be cleared due to chaos from overlapping resonances (Wisdom 1980). Thus debris disk edges set constraints on the possible perturbing planet’s mass and location (see Fig. 4). Their detailed shape can also be a powerful indicator of the mass of the planet sculpting the disk; lower mass planets cause sharper edges (Chiang et al. 2009), although this shape also depends on planetesimal (and planet) eccentricity (Mustill and Wyatt 2012). The existence of planetary systems inside debris rings would be a natural explanation for the dearth of planetesimals there (see Fig. 4), requiring typically around 5 Neptune mass planets (Faber and Quillen 2007). Planets may also be responsible for carving wide gaps in broad debris disks, with gap sizes indicative of the total number and masses of planets present (Nesvold and Kuchner 2015; Shannon et al. 2016), although broad gaps can also be carved by secular resonances that sweep through the disk as the protoplanetary disk disperses (Zheng et al. 2017). Planets can also carve very narrow gaps in debris disks at specific mean motion resonances (Tabeshian and Wiegert 2016),

If planets are not responsible for shaping the inner edges of debris disks and for the absence of planetesimals in the inner regions, then another explanation for these features must be sought. Collisional depletion of the inner regions could explain a shallow inner edge at a location determined by the system age and planetesimal size (Kennedy and Wyatt 2010; Schüppler et al. 2016). A preferential location for

planetesimal formation, say at a snowline or dead zone edge in a protoplanetary disk, could also explain an overdensity at a certain location. However, since the location of such transitions in protoplanetary disks evolve with time (Hasegawa and Pudritz 2012; Eistrup et al. 2017), it remains to be seen if these could explain a sharp disk edge for which an element of shepherding is needed. The presence of gas in debris disks has also been proposed as a mechanism to form sharp edges (Lyra and Kuchner 2013; Richert et al. 2017), although it is unclear that sufficient quantities of gas are present.

Scattering: exocomets and scattered disks

It might be expected that scattering of planetesimals by a planetary system is only relevant in the earliest phases of evolution, because objects that can have close encounters with planets are short-lived (e.g., comets leaving the Kuiper belt in the Solar System have a dynamical lifetime of ~ 45 Myr, Levison and Duncan 1997). However, for low mass planets in the outer regions of disks scattering timescales can be longer than the system age, allowing a long-lived scattered disk of primordial planetesimals and the possibility that planet-mass bodies could reside within debris disks (Wyatt et al. 2017). This could result in a continual injection of planetesimals into a planetary system (e.g., Muñoz-Gutiérrez et al. 2015), thus replenishing a population of exocomets that need not be massive to be detectable.

There is a growing body of observational evidence for hot dust in the inner regions of planetary systems, with debate ongoing as to whether this originates in in-situ asteroid belts (which is possible if the belts are beyond a few au, Wyatt et al. 2007b; Geiler and Krivov 2017), dust dragged in from the outer belt by Poynting-Robertson drag (which is a plausible explanation for the low 0.1-1% excess levels of hot dust seen by KIN, Wyatt 2005b; Mennesson et al. 2014), recent giant impacts between planetary embryos (which is the preferred explanation for extreme $\gg 10\%$ levels of hot dust that are found predominantly around < 100 Myr stars, Wyatt and Jackson 2016), or the destruction of exocomets scattered in from an outer belt (which is supported by the presence of CO gas in one system with moderate $\sim 10\%$ excess levels, see Fig. 4, Marino et al. 2017b). Exocomets passing in front of the star are also the preferred explanation for the variable gas absorption seen toward β Pictoris (Beust and Morbidelli 1996; Kiefer et al. 2014), and for dips in the light curves of some main sequence stars (Boyajian et al. 2016; Rappaport et al. 2017).

Exocometary activity may be expected at some level in all systems in which a planetary system interacts with a planetesimal belt, e.g., through either exterior or interior resonances (Faramaz et al. 2017). However, for some systems exocometary scattering may be more efficient, and it is such systems that are likely to have the highest levels of observed exocometary dust (e.g., like η Corvi, Fig. 4). The efficiency with which a planetary system passes exocomets in from an outer belt has been studied both numerically and analytically, leading to the conclusion that closely packed systems of low mass planets are the most efficient (Bonsor et al.

2012), and highlighting the importance of the lack of massive planet that is an efficient ejector (see Fig. 4, Wyatt et al. 2017). While this might suggest that the super-Earth planetary systems discovered by *Kepler* are efficient exocomet scatterers, the planet chain must also extend out as far as a long-lived source population of comets, which as noted earlier must likely reside > 30 au to survive for Gyr against collisional depletion. Young planetary systems may host an exocomet population that is a residual of their formation process (which hence could potentially be a valuable probe of that process), but any such exocomet population will decrease over time as planetesimals are removed by scattering. Ways to maintain an exocomet population over Gyr timescales have also been sought, e.g., by allowing a planet to migrate into a disk (Bonsor et al. 2014) or by witnessing the aftermath of a dynamical instability (Bonsor et al. 2013). For now the interpretation of hot debris has many uncertainties, but since this dust (and the planetesimals from which it originates) must pass through the planetary system, the architecture of those planets is inevitably imprinted on both the level, radial distribution and asymmetrical structure of the dust.

Witnessing ongoing planet formation

Planet formation processes are thought to take place predominantly during the protoplanetary disk phase, since that is when the circumstellar disk contains sufficient mass in both dust and gas to form planets (see Fig. 1). By the debris disk phase, observations show that any significant solid mass must be either in planetesimals or planets, and the gas content is also believed to be relatively limited (but see above). Nevertheless, the processes associated with planet formation can continue in the absence of a protoplanetary disk. For example, planetesimals may continue to grow into dwarf planets, and planets may also continue to grow through collisions or accretion of gas. Similarly, the planetary system that emerges from the protoplanetary disk may undergo significant evolution (e.g., through dynamical instability or planet migration). Evidence for all of these processes may be imprinted on the debris disk.

Continued growth of dwarf planets

What stirs a debris disk is unknown, that is, why the planetesimals collide at sufficient velocity to break apart. It might be thought more likely that planetesimals formed in a low collision velocity environment, since this would aid their growth, and regardless of their formation mechanism, gas drag would act to damp collision velocities while in the protoplanetary disk. Perhaps the neatest explanation is that a debris disk stirs itself. In a series of papers, Kenyon and Bromley (2002, 2008, 2010) showed how a disk containing only planetesimals colliding at low velocity would eventually grow Pluto-sized objects that stir the disk in its vicinity causing

a collisional cascade and the ultimate destruction of the debris disk. Since growth timescales are longer further from the star, this leads to the prediction that a broad planetesimal disk would appear as a bright ring of emission that propagates out to the edge of the disk over Gyr timescales.

There is, however, no evidence to corroborate this picture. For example, observations of how disk brightness decreases with stellar age show that, on a population level, the observations are consistent with stars being born with narrow debris belts that are pre-stirred by the time the protoplanetary disk disperses (Kennedy and Wyatt 2010). If there is any evidence for disks having larger radii around older stars, it is consistent with the smaller radii disks being collisionally depleted below the detection threshold, and inconsistent with seeing different parts of a broad disk at different epochs. Nevertheless, these studies show that the growth of dwarf planets would occur naturally if protoplanetary disks leave behind unstirred planetesimal disks. This picture is also consistent with the observed debris disk populations (e.g., Fig. 2) as long as the planetesimals are usually confined to narrow rings, although it would still be necessary to invoke some other stirring agent to explain the very young < 20 Myr debris disks seen at 10s of au, which seem to be stirred on much shorter timescales than permitted by the model (Milli et al. 2017).

Giant impacts at 10s of au

Disk structure provides an alternative test for the possible growth of dwarf planets within debris disks. Such planets grow through multiple collisions between dwarf planet embryos that would be expected to release significant quantities of dust that should be readily detectable. While the resulting cloud of unbound debris would appear as an expanding clump on short timescales that is unlikely to be detected (Wyatt and Dent 2002), the resulting structure would be asymmetric for many 1000s of orbits due to the passage of the debris through the point in space at which the impact occurred (Jackson et al. 2014; Kral et al. 2015). This results in a significantly increased collision rate at this point (and is thus where dust and gas is produced most vigorously) and translates into detectable asymmetric structures for Myr for collisions in the outer regions of the disk.

This was suggested as the origin of the dust and gas clump in the β Pictoris disk (Dent et al. 2014), although the tentative orbital motion of the clump (Li et al. 2012) and the broad radial structure of the clump (Matrà et al. 2017a) now disfavors this explanation. Giant impacts in the outer regions of debris disks have also been proposed as the origin of structures in the HD181327 and HD61005 disks (Stark et al. 2014; Olofsson et al. 2016). Such structures are inevitable at some level and frequency if large planetesimals and dwarf planets are present in debris disks. Thus if these features are not observed this would be informative about the maximum number of dwarf planets that could be present.

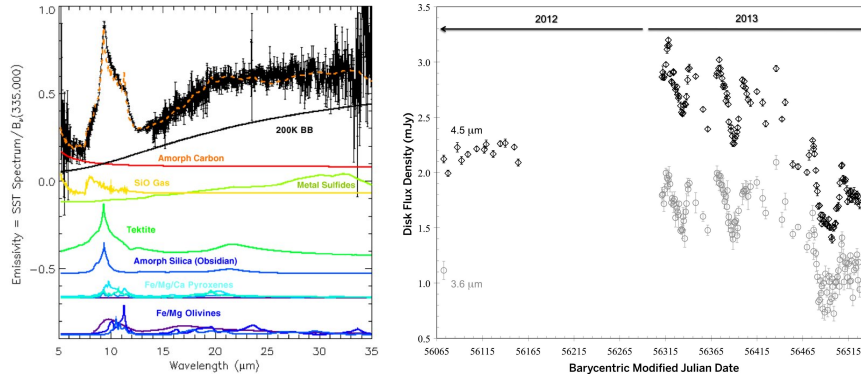


Fig. 5 Spectral information (left, Lisse et al. 2009) and temporal evolution (right, Meng et al. 2014) of the infrared emission from some young stars provides the strongest evidence for giant impacts in the terrestrial planet region. The spectrum is that of the 22 Myr A3V star HD172555 for which modelling shows evidence for the amorphous silica expected to be produced in a high velocity collision. The rapid cyclical evolution in brightness of the 35 Myr G6V star ID8 is consistent with that expected from an optically thick clump of debris produced in a collision.

Giant impacts in the terrestrial planet region

In contrast to the long-lived asymmetries at large distance from the star, the asymmetric structures from debris from giant impacts that occur within a few au should be short-lived. However, such giant impact debris is still potentially readily detectable (e.g., Genda et al. 2015). This is because it takes only an asteroid's worth of dust to be detectable (e.g., Kenyon and Bromley 2005), and because this region is observed to be commonly empty of dust following dispersal of the protoplanetary disk (see Fig. 2).

Moreover, the standard model for terrestrial planet formation involves many such impacts in the timeframe 10-100 Myr (Kenyon and Bromley 2008), with the collision that formed the Earth's moon being a good example from the Solar System (see Wyatt and Jackson 2016, for a review of giant impacts). The level of dust emission expected from debris created in the Moon-forming collision can be calculated (Jackson and Wyatt 2012), but there remains significant uncertainty in the duration of detectability. For example, it is expected that $\sim 30\%$ of the debris comes off as vapor that recondenses into cm-size grains that are both bright and short-lived (a few 1000 orbits), while the remainder comes off as large boulders that collisionally grind down and reaccrete onto the Earth and Venus over ~ 15 Myr. Thus the duration of detectability can be anywhere in the range $10^3 - 10^7$ Myr depending on the details of the boulder size distribution which is poorly constrained, as well as the dust optical properties.

Nevertheless, observationally it can be said that 3% of nearby Sun-like stars in the age range 10-120 Myr show large levels of hot emission at $12 \mu\text{m}$ (which must originate from dust within a few au, Kennedy and Wyatt 2013). Warm emission

traced at $24\ \mu\text{m}$ is also prevalent at this epoch (Meng et al. 2017). In many cases it is hard to argue that this dust emission cannot be attributed to a massive young asteroid belt. However, in others there is evidence to support a giant impact origin for the dust. For example, in HD172555 the infrared spectrum shows spectral features indicative of the composition of the dust, which is inferred to be primarily silica (see Fig. 5, Lisse et al. 2009), a composition expected to be produced in a hypervelocity impact. For others, temporal evolution of the thermal emission is seen that may be attributed to the orbital motion of a clump of vapour condensates (see Fig. 5, Meng et al. 2014, 2015). These observations can potentially be used to characterise the aftermath of giant impacts, that is, the size distribution of the fragments, their composition and their orbital properties.

Frequency of terrestrial planet formation

Exoplanet surveys cannot yet tell us the fraction of stars that have Earth-like planets, or the fraction that undergo terrestrial planet formation in the same way as the Solar System. While the fraction of stars with Earth-like planets has been estimated by some authors to be just a few %, we know that super-Earth like planets (i.e., planets more massive than the Earth but residing much closer to the star) are common, being found around 30-50% of stars (e.g., see Winn and Fabrycky 2015). The frequency with which bright levels of hot dust are detected has the potential to say when (and where) giant impacts occur, and so provides valuable information about the fraction of stars for which this mode of planet formation operates.

Despite a few attempts (e.g., Rhee et al. 2008; Wyatt and Jackson 2016), it is hard to come to concrete conclusions yet from the incidence of hot infrared excesses, primarily because such conclusions rely on assumptions about the size distribution of the giant impact debris and the fraction of infrared excesses that originate in giant impacts rather than asteroid belts (see above). Wyatt et al. (2017) considered a different way of using the statistical information, arguing that there is a sweet-spot in the mass and semimajor axis of the planet for which its giant impact debris lasts longest above detectable levels (see orange contours on Fig. 4 right). This sweet-spot depends on details of the observation being performed, but generally requires planets of a few M_{\oplus} at a few au. The inferred examples of giant impact debris found around A stars (like that in Fig. 5 left) are consistent with the expectation that this should be commonly found at temperatures appropriate for this sweet-spot, whereas the giant impact debris found around Sun-like stars (like that in Fig. 5 right) is inferred to be at a fraction of an au. This could suggest that terrestrial planet formation is rare beyond 1 au around Sun-like stars, and that the examples of giant impact debris around such stars originate in the formation of super-Earths. There are no examples of giant impact debris around M stars, which may be due to the short duration of detectability for such emission, rather than an absence of giant impacts around M stars (Wyatt et al. 2017).

Conclusions

Debris disks provide valuable information about planet formation processes, either by characterising the dispersal of the protoplanetary disk in which such processes take place, by detailing the outcome of planetesimal and planet formation both in individual systems and on a population level, or by bearing witness to such processes in action.

There is a growing number of detections of gas in debris disks. The large gas masses and radial structure suggest that for some systems (particularly 10 – 40 Myr A stars) primordial gas may persist after protoplanetary disk dispersal. Lower levels of secondary gas are also now found to be common, requiring a volatile composition for the planetesimals that is similar to Solar System comets. Planetesimal formation at > 10 au occurs in at least 20% of systems, with typically $> 1M_{\oplus}$ left in > 10 km planetesimals at > 10 au. It is hard to assess if the remaining 80% of stars were inefficient at forming planetesimals, or if their planetesimals have been depleted (perhaps because they only formed closer to the star). Debris disks also provide clues to the level of stirring within the disks, which is sometimes low ($e < 0.01$), and also suggest a dependence of planetesimal properties on stellar mass.

Many of the ways in which planets impose structure on debris disks have been characterised, and these compare favourably with structures seen in the growing number of debris disk images. In some cases the putative perturbing planet has been identified through other means confirming this interpretation. However, more such examples are needed before debris disk structure can be used with confidence to predict unseen planets. For example, regions that are empty of dust could be cleared by orbiting planets, but could equally be regions of inefficient planetesimal formation. In the meantime, disk structures (particularly asymmetries) provide compelling evidence in favour of planets and can be used to set constraints on any such planets' masses and orbits and in some cases their dynamical histories. The first statistical evidence is also accumulating to link the properties of outer planetesimal belts to the properties of inner planetary systems, though it is unclear as yet if this link is direct (through planet-disk interactions) or indirect (through a common formation environment).

Ongoing planet formation processes are also expected to have a characteristic signature in debris disk observations. This could be through the slow growth of Pluto-sized bodies resulting in bright rings of debris at 10s of au up to Gyr, a long-lived asymmetric disk resulting from giant collisions in this outer disk, or the release of large quantities of dust within a few au from the giant impacts expected between planetary embryos during terrestrial planet formation. The strongest evidence for ongoing planet formation comes from spectral and temporal observations of a few young hot dust systems that characterise the aftermath of giant impacts. Such detections have implications for the frequency of the formation of terrestrial planet and super-Earths and its mode (i.e., whether this takes place through giant impacts). However, uncertainties in the size distribution of giant impact debris and the possibility that hot dust could also originate in massive asteroid belts (rather than single impacts), means that no firm conclusions can yet be made.

Cross-References

- Andrews & Birnstiel chapter on *Dust evolution in protoplanetary disks*
- Bergin chapter on *Chemistry in protoplanetary disks*
- Kalas chapter on *Fomalhaut's dust debris belt and eccentric planet*
- Kral et al. chapter on *Circumstellar discs: What will be next?*
- Morbidelli chapter on *Dynamical evolution of planetary systems*
- Pudritz et al. chapter on *Connecting planetary composition to formation*

References

- Augereau JC, Nelson RP, Lagrange AM, Papaloizou JCB, Mouillet D (2001) Dynamical modeling of large scale asymmetries in the beta Pictoris dust disk. *A&A*370:447–455
- Beust H, Morbidelli A (1996) Mean-Motion Resonances as a Source for Infalling Comets toward β Pictoris. *Icarus*120:358–370
- Beust H, Augereau JC, Bonsor A et al. (2014) An independent determination of Fomalhaut b's orbit and the dynamical effects on the outer dust belt. *A&A*561:A43
- Bonsor A, Augereau JC, Thébaud P (2012) Scattering of small bodies by planets: a potential origin for exozodiacal dust? *A&A*548:A104
- Bonsor A, Raymond SN, Augereau JC (2013) The short-lived production of exozodiacal dust in the aftermath of a dynamical instability in planetary systems. *MNRAS*433:2938–2945
- Bonsor A, Raymond SN, Augereau JC, Ormel CW (2014) Planetesimal-driven migration as an explanation for observations of high levels of warm, exozodiacal dust. *MNRAS*441:2380–2391
- Booth M, Kennedy G, Sibthorpe B et al. (2013) Resolved debris discs around A stars in the Herschel DEBRIS survey. *MNRAS*428:1263–1280
- Booth M, Dent WRF, Jordán A et al. (2017) The Northern arc of ϵ Eridani's Debris Ring as seen by ALMA. *MNRAS*469:3200–3212
- Bowler BP (2016) Imaging Extrasolar Giant Planets. *PASP*128(10):102,001
- Boyajian TS, LaCourse DM, Rappaport SA et al. (2016) Planet Hunters IX. KIC 8462852 - where's the flux? *MNRAS*457:3988–4004
- Brandeker A, Cataldi G, Olofsson G et al. (2016) Herschel detects oxygen in the β Pictoris debris disk. *A&A*591:A27
- Bryden G, Beichman CA, Carpenter JM et al. (2009) Planets and Debris Disks: Results from a Spitzer/MIPS Search for Infrared Excess. *ApJ*705:1226–1236
- Carpenter JM, Mamajek EE, Hillenbrand LA, Meyer MR (2009) Debris Disks in the Upper Scorpius OB Association. *ApJ*705:1646–1671
- Carrera D, Gorti U, Johansen A, Davies MB (2017) Planetesimal Formation by the Streaming Instability in a Photoevaporating Disk. *ApJ*839:16
- Chen CH, Mittal T, Kuchner M et al. (2014) The Spitzer Infrared Spectrograph Debris Disk Catalog. I. Continuum Analysis of Unresolved Targets. *ApJS*211:25
- Chiang E, Kite E, Kalas P, Graham JR, Clampin M (2009) Fomalhaut's Debris Disk and Planet: Constraining the Mass of Fomalhaut b from disk Morphology. *ApJ*693:734–749
- Cieza LA, Olofsson J, Harvey PM et al. (2013) The Herschel DIGIT Survey of Weak-line T Tauri Stars: Implications for Disk Evolution and Dissipation. *ApJ*762:100
- Currie T, Lisse CM, Kuchner M et al. (2015) Direct Imaging and Spectroscopy of a Young Extrasolar Kuiper Belt in the Nearest OB Association. *ApJ*807:L7
- Dent WRF, Wyatt MC, Roberge A et al. (2014) Molecular Gas Clumps from the Destruction of Icy Bodies in the β Pictoris Debris Disk. *Science* 343:1490–1492

- Eiroa C, Marshall JP, Mora A et al. (2013) DUst around NEarby Stars. The survey observational results. *A&A*555:A11
- Eistrup C, Walsh C van Dishoeck EF (2017) Molecular abundances and C/O ratios in chemically evolving planet-forming disk midplanes. ArXiv e-prints
- Ercolano B, Jennings J, Rosotti G Birnstiel T (2017) X-ray photoevaporation's limited success in the formation of planetesimals by the streaming instability. ArXiv e-prints
- Faber P Quillen AC (2007) The total number of giant planets in debris discs with central clearings. *MNRAS*382:1823–1828
- 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. *MNRAS*465:2352–2365
- Fischer DA Valenti J (2005) The Planet-Metallicity Correlation. *ApJ*622:1102–1117
- Gáspár A, Rieke GH Balog Z (2013) The Collisional Evolution of Debris Disks. *ApJ*768:25
- Gáspár A, Rieke GH Ballering N (2016) The Correlation between Metallicity and Debris Disk Mass. *ApJ*826:171
- Geiler F Krivov AV (2017) Does warm debris dust stem from asteroid belts? *MNRAS*468:959–970
- Genda H, Kobayashi H Kokubo E (2015) Warm Debris Disks Produced by Giant Impacts during Terrestrial Planet Formation. *ApJ*810:136
- Golimowski DA, Krist JE, Stapelfeldt KR et al. (2011) Hubble and Spitzer Space Telescope Observations of the Debris Disk around the nearby K Dwarf HD 92945. *AJ*142:30
- Greaves JS Wyatt MC (2003) Some anomalies in the occurrence of debris discs around main-sequence A and G stars. *MNRAS*345:1212–1222
- Greaves JS, Holland WS, Matthews BC et al. (2016) Gas and dust around A-type stars at tens of Myr: signatures of cometary breakup. *MNRAS*461:3910–3917
- Hardy A, Caceres C, Schreiber MR et al. (2015) Probing the final stages of protoplanetary disk evolution with ALMA. *A&A*583:A66
- Hasegawa Y Pudritz RE (2012) Evolutionary Tracks of Trapped, Accreting Protoplanets: The Origin of the Observed Mass-Period Relation. *ApJ*760:117
- Heng K Tremaine S (2010) Long-lived planetesimal discs. *MNRAS*401:867–889
- Hughes AM, Wilner DJ, Mason B et al. (2012) Confirming the Primarily Smooth Structure of the Vega Debris Disk at Millimeter Wavelengths. *ApJ*750:82
- Hughes AM, Lieman-Sifry J, Flaherty KM et al. (2017) Radial Surface Density Profiles of Gas and Dust in the Debris Disk around 49 Ceti. *ApJ*839:86
- Jackson AP Wyatt MC (2012) Debris from terrestrial planet formation: the Moon-forming collision. *MNRAS*425:657–679
- Jackson AP, Wyatt MC, Bonsor A Veras D (2014) Debris from giant impacts between planetary embryos at large orbital radii. *MNRAS*440:3757–3777
- Kaib NA, White EB Izidoro A (2017) Simulations of the Fomalhaut System Within Its Local Galactic Environment. ArXiv e-prints
- Kains N, Wyatt MC Greaves JS (2011) Steady-state evolution of debris discs around solar-type stars. *MNRAS*414:2486–2497
- Kalas P, Graham JR, Fitzgerald MP Clampin M (2013) STIS Coronagraphic Imaging of Fomalhaut: Main Belt Structure and the Orbit of Fomalhaut b. *ApJ*775:56
- Kennedy GM Wyatt MC (2010) Are debris discs self-stirred? *MNRAS*405:1253–1270
- Kennedy GM Wyatt MC (2013) The bright end of the exo-Zodi luminosity function: disc evolution and implications for exo-Earth detectability. *MNRAS*433:2334–2356
- Kennedy GM Wyatt MC (2014) Do two-temperature debris discs have multiple belts? *MNRAS*444:3164–3182
- Kenyon SJ Bromley BC (2002) Dusty Rings: Signposts of Recent Planet Formation. *ApJ*577:L35–L38
- Kenyon SJ Bromley BC (2005) Prospects for Detection of Catastrophic Collisions in Debris Disks. *AJ*130:269–279
- Kenyon SJ Bromley BC (2008) Variations on Debris Disks: Icy Planet Formation at 30-150 AU for 1-3 M_{\oplus} Main-Sequence Stars. *ApJS*179:451–483

- Kenyon SJ Bromley BC (2010) Variations on Debris Disks. II. Icy Planet Formation as a Function of the Bulk Properties and Initial Sizes of Planetesimals. *ApJS*188:242–279
- Kiefer F, Lecavelier des Etangs A, Boissier J et al. (2014) Two families of exocomets in the β Pictoris system. *Nature*514:462–464
- Kóspál Á, Moór A, Juhász A et al. (2013) ALMA Observations of the Molecular Gas in the Debris Disk of the 30 Myr Old Star HD 21997. *ApJ*776:77
- Kral Q, Thébault P, Augereau JC, Boccaletti A Charnoz S (2015) Signatures of massive collisions in debris discs. A self-consistent numerical model. *A&A*573:A39
- Kral Q, Wyatt M, Carswell RF et al. (2016) A self-consistent model for the evolution of the gas produced in the debris disc of β Pictoris. *MNRAS*461:845–858
- Kral Q, Matrà L, Wyatt MC Kennedy GM (2017) Predictions for the secondary CO, C and O gas content of debris discs from the destruction of volatile-rich planetesimals. *MNRAS*469:521–550
- Krijt S Kama M (2014) A dearth of small particles in debris disks. An energy-constrained smallest fragment size. *A&A*566:L2
- Krivov AV, Löhne T Sremčević M (2006) Dust distributions in debris disks: effects of gravity, radiation pressure and collisions. *A&A*455:509–519
- Krivov AV, Eiroa C, Löhne T et al. (2013) Herschel’s “Cold Debris Disks”: Background Galaxies or Quiescent Rims of Planetary Systems? *ApJ*772:32
- Krivov AV, Ide A, Löhne T, Johansen A Blum J (2018) Debris disc constraints on planetesimal formation. *MNRAS*474:2564–2575
- Lagrange AM, Bonnefoy M, Chauvin G et al. (2010) A Giant Planet Imaged in the Disk of the Young Star β Pictoris. *Science* 329:57
- Lee EJ Chiang E (2016) A Primer on Unifying Debris Disk Morphologies. *ApJ*827:125
- Levison HF Duncan MJ (1997) From the Kuiper Belt to Jupiter-Family Comets: The Spatial Distribution of Ecliptic Comets. *Icarus*127:13–32
- Li D, Telesco CM Wright CM (2012) The Mineralogy and Structure of the Inner Debris Disk of β Pictoris. *ApJ*759:81
- Lieman-Sifry J, Hughes AM, Carpenter JM et al. (2016) Debris Disks in the Scorpius-Centaurus OB Association Resolved by ALMA. *ApJ*828:25
- Lisse CM, Chen CH, Wyatt MC et al. (2009) Abundant Circumstellar Silica Dust and SiO Gas Created by a Giant Hypervelocity Collision in the \sim 12 Myr HD172555 System. *ApJ*701:2019–2032
- Löhne T, Krivov AV Rodmann J (2008) Long-Term Collisional Evolution of Debris Disks. *ApJ*673:1123–1137
- Löhne T, Krivov AV, Kirchschrager F, Sende JA Wolf S (2017) Collisions and drag in debris discs with eccentric parent belts. *A&A*605:A7
- Lyra W Kuchner M (2013) Formation of sharp eccentric rings in debris disks with gas but without planets. *Nature*499:184–187
- MacGregor MA, Wilner DJ, Chandler C et al. (2016) Constraints on Planetesimal Collision Models in Debris Disks. *ApJ*823:79
- MacGregor MA, Matrà L, Kalas P et al. (2017) A Complete ALMA Map of the Fomalhaut Debris Disk. *ApJ*842:8
- Marino S, Matrà L, Stark C et al. (2016) Exocometary gas in the HD 181327 debris ring. *MNRAS*460:2933–2944
- Marino S, Wyatt MC, Kennedy GM et al. (2017a) ALMA observations of the multiplanet system 61 Vir: what lies outside super-Earth systems? *MNRAS*469:3518–3531
- Marino S, Wyatt MC, Panić O et al. (2017b) ALMA observations of the η Corvi debris disc: inward scattering of CO-rich exocomets by a chain of 3–30 M_{\oplus} planets? *MNRAS*465:2595–2615
- Matrà L, Dent WRF, Wyatt MC et al. (2017a) Exocometary gas structure, origin and physical properties around β Pictoris through ALMA CO multitransition observations. *MNRAS*464:1415–1433

- Matrà L, MacGregor MA, Kalas P et al. (2017b) Detection of Exocometary CO within the 440 Myr Old Fomalhaut Belt: A Similar CO+CO₂ Ice Abundance in Exocomets and Solar System Comets. *ApJ*842:9
- Matrà L, Wilner DJ, Öberg KI et al. (2018) Molecular Reconnaissance of the β Pictoris Gas Disk with the SMA: A Low HCN/(CO+CO₂) Outgassing Ratio and Predictions for Future Surveys. *ApJ*853:147
- Matthews BC, Krivov AV, Wyatt MC, Bryden G Eiroa C (2014) Observations, Modeling, and Theory of Debris Disks. *Protostars and Planets VI* pp 521–544
- Meng HYA, Su KYL, Rieke GH et al. (2014) Large impacts around a solar-analog star in the era of terrestrial planet formation. *Science* 345:1032–1035
- Meng HYA, Su KYL, Rieke GH et al. (2015) Planetary Collisions Outside the Solar System: Time Domain Characterization of Extreme Debris Disks. *ApJ*805:77
- Meng HYA, Rieke GH, Su KYL Gáspár A (2017) The First 40 Million Years of Circumstellar Disk Evolution: The Signature of Terrestrial Planet Formation. *ApJ*836:34
- Mennesson B, Millan-Gabet R, Serabyn E et al. (2014) Constraining the Exozodiacal Luminosity Function of Main-sequence Stars: Complete Results from the Keck Nuller Mid-infrared Surveys. *ApJ*797:119
- Milli J, Vigan A, Mouillet D et al. (2017) Near-infrared scattered light properties of the HR 4796 A dust ring. A measured scattering phase function from 13.6deg to 166.6deg. *A&A*599:A108
- Moór A, Curé M, Kóspál Á et al. (2017) Molecular gas in debris disks around young A-type stars. *ArXiv e-prints*
- Morey É Lestrade JF (2014) On the steady state collisional evolution of debris disks around M dwarfs. *A&A*565:A58
- Moro-Martín A, Marshall JP, Kennedy G et al. (2015) Does the Presence of Planets Affect the Frequency and Properties of Extrasolar Kuiper Belts? Results from the Herschel Debris and Dunes Surveys. *ApJ*801:143
- Muñoz-Gutiérrez MA, Pichardo B, Reyes-Ruiz M Peimbert A (2015) Dynamical Heating Induced by Dwarf Planets on Cold Kuiper Belt-like Debris Disks. *ApJ*811:L21
- Mustill AJ Wyatt MC (2009) Debris disc stirring by secular perturbations from giant planets. *MNRAS*399:1403–1414
- Mustill AJ Wyatt MC (2012) Dependence of a planet’s chaotic zone on particle eccentricity: the shape of debris disc inner edges. *MNRAS*419:3074–3080
- Nesvold ER Kuchner MJ (2015) Gap Clearing by Planets in a Collisional Debris Disk. *ApJ*798:83
- Nesvold ER, Naoz S Fitzgerald MP (2017) HD 106906: A Case Study for External Perturbations of a Debris Disk. *ApJ*837:L6
- Olofsson J, Samland M, Avenhaus H et al. (2016) Azimuthal asymmetries in the debris disk around HD 61005. A massive collision of planetesimals? *A&A*591:A108
- Pan M, Nesvold ER Kuchner MJ (2016) Apocenter Glow in Eccentric Debris Disks: Implications for Fomalhaut and ϵ Eridani. *ApJ*832:81
- Panić O, Holland WS, Wyatt MC et al. (2013) First results of the SONS survey: submillimetre detections of debris discs. *MNRAS*435:1037–1046
- Pawellek N, Krivov AV, Marshall JP et al. (2014) Disk Radii and Grain Sizes in Herschel-resolved Debris Disks. *ApJ*792:65
- Pearce TD Wyatt MC (2014) Dynamical evolution of an eccentric planet and a less massive debris disc. *MNRAS*443:2541–2560
- Pearce TD Wyatt MC (2015) Double-ringed debris discs could be the work of eccentric planets: explaining the strange morphology of HD 107146. *MNRAS*453:3329–3340
- Péricaud J, Di Folco E, Dutrey A, Guilloteau S Piétu V (2017) The hybrid disks: a search and study to better understand evolution of disks. *A&A*600:A62
- Phillips NM, Greaves JS, Dent WRF et al. (2010) Target selection for the SUNS and DEBRIS surveys for debris discs in the solar neighbourhood. *MNRAS*403:1089–1101
- Rappaport S, Vanderburg A, Jacobs T et al. (2017) Likely Transiting Exocomets Detected by Kepler. *ArXiv e-prints*

- Raymond SN, Armitage PJ, Moro-Martín A et al. (2011) Debris disks as signposts of terrestrial planet formation. *A&A*530:A62
- Rhee JH, Song I, Zuckerman B (2008) Warm Dust in the Terrestrial Planet Zone of a Sun-like Pleiades Star: Collisions between Planetary Embryos? *ApJ*675:777-783
- Ricci L, Carpenter JM, Fu B et al. (2015) ALMA Observations of the Debris Disk around the Young Solar Analog HD 107146. *ApJ*798:124
- Richert AJW, Lyra W, Kuchner M (2017) The interplay between radiation pressure and the photoelectric instability in optically thin disks of gas and dust. *ArXiv e-prints*
- Schneider A, Song I, Melis C et al. (2013) The Nearby, Young, Isolated, Dusty Star HD 166191. *ApJ*777:78
- Schüppler C, Krivov AV, Löhne T et al. (2016) Origin and evolution of two-component debris discs and an application to the α Eridani system. *MNRAS*461:2146-2154
- Shannon A, Clarke C, Wyatt M (2014) Dancing with the stars: formation of the Fomalhaut triple system and its effect on the debris discs. *MNRAS*442:142-147
- Shannon A, Bonsor A, Kral Q, Matthews E (2016) The unseen planets of double belt debris disc systems. *MNRAS*462:L116-L120
- Smith R, Wyatt MC, Dent WRF (2008) The nature of mid-infrared excesses from hot dust around Sun-like stars. *A&A*485:897-915
- Stark CC, Schneider G, Weinberger AJ et al. (2014) Revealing Asymmetries in the HD 181327 Debris Disk: A Recent Massive Collision or Interstellar Medium Warping. *ApJ*789:58
- Strubbe LE, Chiang EI (2006) Dust Dynamics, Surface Brightness Profiles, and Thermal Spectra of Debris Disks: The Case of AU Microscopii. *ApJ*648:652-665
- Su KYL, Rieke GH, Malhotra R et al. (2013) Asteroid Belts in Debris Disk Twins: Vega and Fomalhaut. *ApJ*763:118
- Tabeshian M, Wiegert PA (2016) Detection and Characterization of Extrasolar Planets through Mean-motion Resonances. I. Simulations of Hypothetical Debris Disks. *ApJ*818:159
- Takeuchi T, Artymowicz P (2001) Dust Migration and Morphology in Optically Thin Circumstellar Gas Disks. *ApJ*557:990-1006
- Tamayo D (2014) Consequences of an eccentric orbit for Fomalhaut b. *MNRAS*438:3577-3586
- Telesco CM, Fisher RS, Wyatt MC et al. (2005) Mid-infrared images of β Pictoris and the possible role of planetesimal collisions in the central disk. *Nature*433:133-136
- Thébaud P, Wu Y (2008) Outer edges of debris discs. How sharp is sharp? *A&A*481:713-724
- Thureau ND, Greaves JS, Matthews BC et al. (2014) An unbiased study of debris discs around A-type stars with Herschel. *MNRAS*445:2558-2573
- Vitense C, Krivov AV, Kobayashi H, Löhne T (2012) An improved model of the Edgeworth-Kuiper debris disk. *A&A*540:A30
- Wadhwa M, Amelin Y, Davis AM et al. (2007) From Dust to Planetesimals: Implications for the Solar Protoplanetary Disk from Short-lived Radionuclides. *Protostars and Planets V* pp 835-848
- Winn JN, Fabrycky DC (2015) The Occurrence and Architecture of Exoplanetary Systems. *ARA&A*53:409-447
- Wisdom J (1980) The resonance overlap criterion and the onset of stochastic behavior in the restricted three-body problem. *AJ*85:1122-1133
- Wyatt MC (2003) Resonant Trapping of Planetesimals by Planet Migration: Debris Disk Clumps and Vega's Similarity to the Solar System. *ApJ*598:1321-1340
- Wyatt MC (2005a) Spiral structure when setting up pericentre glow: possible giant planets at hundreds of AU in the HD 141569 disk. *A&A*440:937-948
- Wyatt MC (2005b) The insignificance of P-R drag in detectable extrasolar planetesimal belts. *A&A*433:1007-1012
- Wyatt MC (2006) Dust in Resonant Extrasolar Kuiper Belts: Grain Size and Wavelength Dependence of Disk Structure. *ApJ*639:1153-1165
- Wyatt MC (2008) Evolution of Debris Disks. *ARA&A*46:339-383
- Wyatt MC, Dent WRF (2002) Collisional processes in extrasolar planetesimal discs - dust clumps in Fomalhaut's debris disc. *MNRAS*334:589-607

- Wyatt MC Jackson AP (2016) Insights into Planet Formation from Debris Disks. II. Giant Impacts in Extrasolar Planetary Systems. *Space Sci Rev*205:231–265
- Wyatt MC, Dermott SF, Telesco CM et al. (1999) How Observations of Circumstellar Disk Asymmetries Can Reveal Hidden Planets: Pericenter Glow and Its Application to the HR 4796 Disk. *ApJ*527:918–944
- Wyatt MC, Clarke CJ Greaves JS (2007a) Origin of the metallicity dependence of exoplanet host stars in the protoplanetary disc mass distribution. *MNRAS*380:1737–1743
- Wyatt MC, Smith R, Greaves JS et al. (2007b) Transience of Hot Dust around Sun-like Stars. *ApJ*658:569–583
- Wyatt MC, Smith R, Su KYL et al. (2007c) Steady State Evolution of Debris Disks around A Stars. *ApJ*663:365–382
- Wyatt MC, Kennedy G, Sibthorpe B et al. (2012) Herschel imaging of 61 Vir: implications for the prevalence of debris in low-mass planetary systems. *MNRAS*424:1206–1223
- Wyatt MC, Panić O, Kennedy GM Matrà L (2015) Five steps in the evolution from protoplanetary to debris disk. *Ap&SS*357:103
- Wyatt MC, Bonsor A, Jackson AP, Marino S Shannon A (2017) How to design a planetary system for different scattering outcomes: giant impact sweet spot, maximizing exocomets, scattered discs. *MNRAS*464:3385–3407
- Zheng X, Lin DNC Kouwenhoven MBN (2017) Planetesimal Clearing and Size-dependent Asteroid Retention by Secular Resonance Sweeping during the Depletion of the Solar Nebula. *ApJ*836:207