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Five steps in the evolution from protoplanetary to debris disk

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Abstract The protoplanetary disks seen around Herbig Ae stars eventually dissipate leaving just a tenuous debris disk, comprised of planetesimals and the dust derived from them, as well as possibly gas and planets. This paper uses the properties of the youngest (10-20 Myr) A star debris disks to consider the transition from protoplanetary to debris disk. It is argued that the physical distinction between these two classes should rest on the presence of primordial gas in sufficient quantities to dominate the motion of small dust grains (rather than on the secondary nature of the dust or its level of stirring). This motivates an observational classification based on the dust emission spectrum which is empirically defined so that A star debris disks require fractional excesses < 3 at $12\,\mu$m and < 2000 at $70\,\mu$m. We also propose that a useful hypothesis to test is that the planet and planetesimal systems seen on the main sequence are already in place during the protoplanetary disk phase, but are obscured or overwhelmed by the rest of the disk. This may be only weakly true if the architecture of the planetary system continues to change until frozen at the epoch of disk dispersal, or completely false if planets and planetesimals form during the relatively short dispersal phase. Five steps in the transition are discussed: **(i)** the well-known carving of an inner hole to form a *transition disk*; **(ii)** depletion of mm-sized dust in the outer disk, where it is noted that it is of critical importance to ascertain whether this mass ends up in larger planetesimals or is collisionally depleted; **(iii)** final clearing of inner regions, where it is noted that multiple debris-like mechanisms exist to replenish moderate levels of hot dust at later phases, and that these likely also operate in protoplanetary disks; **(iv)** disappearence of the gas, noting the recent discoveries of both primordial and secondary gas in debris disks which highlight our ignorance in this area and its impending enlightenment by ALMA; **(v)** formation of ring-like structure of planetesimals, noting that these are shaped by interactions with planets, and that the location of the planetesimals in protoplanetary disks may be unrelated to that of dust concentrations therein that are set by gas interactions.

1 Introduction

While there have been many advances in our understanding of the structure of protoplanetary disks, there remain considerable unknowns, in particular with respect to the status of planet formation within them, and the processes that ultimately make these disks disappear. Protoplanetary disk evolution on Myr timescales is mainly driven by accretion, though photoevaporation may also drive significant mass loss (see Hollenbach et al. 1994), and is especially dominant in the presence of external sources of radiation (e.g., in Orion, Mann et al. 2014). These dispersal processes directly affect the amount of material available for planet formation, and so presumably the eventual architecture of planetary systems, although planet formation processes may themselves also contribute to shaping a disk's structure and evolution, especially in the case that massive planets have formed.

In the innermost regions of protoplanetary disks, gap and hole opening is believed to be the first detectable step away from a continuous primordial disc and towards a more radially concentrated structure, and can be initiated by photoevaporation or planet formation. The first evidence of this inside-out evolution was seen in disks lacking near-infrared excesses (e.g., Strom et al.

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1989; Skrutskie et al. 1990) which were consequently named transition disks. However, the subsequent steps in that evolution are very poorly constrained, especially the relative timescales on which gas and dust dissapear (see, e.g., §3.4).

We know that the end-state of the evolution is for the star to become a main sequence star with (possibly) a remnant debris disk along with a planetary system. Debris disks are discovered like their protoplanetary counterparts by an excess of infrared emission above that expected from the star itself, and because most nearby stars are on the main sequence, their disks can be imaged in great detail and dust detected down to very low levels (Wyatt 2008; Eiroa et al. 2013). The physical picture of debris disks is that the dust we see is continually replenished by collisions between planetesimals in orbit around the star. Thus they are considered to be analogous to the asteroid and Kuiper belts in the Solar System, and as such are usually viewed as being a component of the star's planetary system that formed during the protoplanetary disk phase. This idea is reinforced in several systems in which planets are known in the regions interior to debris disks (Marois et al. 2008; Kalas et al. 2008; Marshall et al. 2014; Rameau et al. 2013).

In this paper we will consider debris disks as descendants of protoplanetary disks and use that perspective to piece together the evolutionary stages that protoplanetary disks must go through after the transition disk phase. In particular we will focus on the properties of the disks at the stage immediately after the protoplanetary disk has dispersed. Section 2 considers the difference between protoplanetary and debris disks, both from an observational and physical point of view. Section 3 then outlines five steps that must occur in the evolution, focussing either on different radial locations, or the evolution of different material components of the disks.

As there are aspects of the evolution that may depend on the mass of the star, either because of how the stellar luminosity affects the disk's evolution (e.g., Kennedy and Kenyon 2009), or because of how the stellar properties affect the detectability of the disk (Wyatt 2008), here we will focus the discussion on the evolution of intermediate mass stars. That is, we will consider the evolution of Herbig Ae (hereafter HAe) stars into main sequence A stars. This choice benefits from A star debris disks being more readily detectable than those around their lower stellar mass counterparts, resulting in better constraints on the structure of their disks around the transition stage. Also, a lot of observational effort in understanding the latter stages of protoplanetary disk evolution has focused on HAe stars, which are generaly brighter than their lower mass T Tauri star counterparts. However, a downside is that HAes are rare and diverse in their ages and formation environment, and they therefore do not form an unbiased sample.

2 Difference between protoplanetary and debris disks

There is no formal distinction between protoplanetary and debris disks, as will become clear in this section. A crude categorisation can be achieved based solely on the age of the host star, with the division at roughly 10 Myr. However, there are counter-examples on either side of this division; e.g., there are examples of 30 Myr-old protoplanetary disks (Scicluna et al. 2014), and of debris disks in young regions like Upper Sco (Carpenter et al. 2009) and the TWHya Association (Riviere-Marichalar et al. 2013). Indeed, detection of a debris disk at the distance of most pre-main sequence stars (~ 140 pc) is limited by observational capabilities, so it is possible that many of the < 10 Myr stars currently without detectable disks will turn out to have debris disks with deeper observations. A more fundamental difference is the amount of dust; debris disks are usually optically thin whereas protoplanetary disks are optically thick[1], which is also evident as more than an order of magnitude difference in the inferred mass of mm-sized dust (Wyatt et al. 2003; Panić et al. 2013, see §3.2). The radial distribution of the material is also different, with debris disks generally being narrower with large inner holes and protoplanetary disks much broader; though again there are counter-examples such as the transition disk class of protoplanetary disk which are characterised by large inner holes. Crucially the large mass of gas, predominantly primordial H_2, which is the main mass component of a protoplanetary disk, is no longer present in debris disks. Even though the gas in a protoplanetary disk is not always readily detectable, it can still have a strong influence on the structure of the dust disk; e.g., the gas pressure keeps the dust disk vertically thick causing larger excess emission.

2.1 Disks around Herbig Ae stars

While statistical studies of HAe stars suffer from a relatively small number of targets compared to those of lower mass stars, the HAe stars possess brighter disks

[1] In this paper optical depth refers to the fraction of starlight that reaches disk material directly, and so refers to the depth at optical and UV wavelengths along the line-of-sight to the star.

and consequently host some of the best studied protoplanetary disks in terms of their detailed structure. Most of the known HAe stars were first identified as potentially young intermediate-mass stars by Herbig (1960) using the criteria of emission line spectra, regions of heavy obscuration and illumination of a nearby nebulosity. Finkenzeller and Mundt (1984) studied the properties of the stars in the Herbig (1960) sample and established that these had significantly higher infrared excesses than ordinary Be stars, while infrared studies by Dong and Hu (1991) and Berrilli et al. (1992) further confirmed the existence of circumstellar material and so the pre-main sequence nature of these stars, as suspected from their spectral characteristics. Grinin et al. (1989, 1991) pointed out the existence of observationally similar stars to the HAe group, but in relative isolation from nebulosities, which were later included in this denomination. A catalogue summarising this class is given in Thé et al. (1994), and typical ages for HAes were found to be 5-10 Myr (van den Ancker et al. 1997).

These disks are traditionally classified from their infrared spectral slopes into group I and II sources (Meeus et al. 2001), which are interpreted as flared and flat structures, respectively, that are linked to the degree of grain growth and settling in the disks (e.g., Dullemond and Dominik 2004). Millimetre spectral slopes provide further evidence of grain growth in these sources (e.g., Acke et al. 2004). The relatively low level of near-infrared emission in HAe disks suggest that most have inner regions that are relatively empty of dust (Yasui et al. 2014), an interpretation which is confirmed for the disks that have been directly imaged in scattered light (Fukagawa et al. 2006), polarised light (Quanz et al. 2012) or submillimetre emission (Brown et al. 2012). While group II sources tend to have larger grains than those in group I, group II disks are not necessarily at a later evolutionary stage, since there is also a high incidence of transition disks in group I (Maaskant et al. 2013).

Most recently, ALMA has allowed breakthroughs in understanding transitional HAe disks, for example finding asymmetries in the dust distribution outside the gap (van der Marel et al. 2013), large discrepancies between the radial distributions of gas and dust (Pineda et al. 2014; Walsh et al. 2014), and structures associated with the flow of gas across the dust gap (Casassus et al. 2013). Many of these features have been linked to putative planets. For example, studies of planet-disk interactions show that planets can open gaps in the gas disk, significantly disturb the inward flow of gas, and induce pressure waves that result in spiral features propagating through the disk (e.g., Paardekooper 2007). The reaction of dust of different sizes to these gas disk structures explains many of the observed features (e.g., Pinilla et al. 2012).

Here we describe a few HAe sources where the disk structure has been studied in great detail, and which exhibit a range of structural features. While these sources are not necessarily representative, and in no way form an unbiased sample, they will be useful for reference later in the paper.

HD100546: This 8-10 Myr star (van den Ancker et al. 1997) has a disk that still contains significant amounts of gas (Panić et al. 2010; Thi et al. 2013) and its dust mass undoubtedly places it in the group of protoplanetary disks (see §3.2). There is a substantial decrease in gas and dust density inside 10 au seen in spatially resolved observations (Wilner et al. 2003; van der Plas et al. 2009; Quanz et al. 2011) further identifying this as a transition disk, as also inferred from modelling of the Spectral Energy Distribution (SED; Bouwman et al. 2003). Dust is detected interferometrically in the near- and mid-infrared at < 0.7 au (Benisty et al. 2010; Panić et al. 2014), so rather than an empty inner hole this disk has a very wide gap. The gap has often been linked to a putative massive planet at that location ($60 M_{\rm Jup}$, Mulders et al. 2013). Quanz et al. (2013) also report detection of a more distant planet at 69 au, indirect support for which comes from millimetre imaging that shows non-co-spatial dust and gas distributions as expected from interactions with such a planet, with the outer disk (> 60 au) depleted of millimetre dust while still abundant in gas (Pineda et al. 2014; Walsh et al. 2014). Spiral features are seen in scattered light at $\sim$100 au scales out to 350 au. Amongst the numerous observational tracers, strong PAH emission arises from the surface of this disk at a range of radii.

HD141569: This 5 Myr old B9.5 star (Weinberger et al. 2000; Merín et al. 2004) has an infrared excess with a fractional luminosity of 0.0084 (Sylvester et al. 1996) comparable to the most luminous debris disks. However, detections of CO (Zuckerman et al. 1995; Dent et al. 2005) and Polycyclic Aromatic Hydrocarbon (PAH) emission (Keller et al. 2008; Geers et al. 2009) discern this source from debris disks suggesting a younger evolutionary stage, with large amounts of both gas ($10^{-4} M_\odot$, Thi et al. 2014) and small dust (Merín et al. 2004) present. Indeed, its sub-mm dust mass of $0.7 M_\oplus$ (Sandell et al. 2011; Panić et al. 2013) and excess emission over a range of wavelengths suggest that this disk is intermediate between the old evolved protoplanetary disks and very young and luminous debris disks. The CO line profile implies a radially broad (90-250 au) gas distribution (Dent et al. 2005; Thi et al. 2014), with an additional warm component that is detected spectro-astrometrically at 17-50 au (Brittain and Rettig 2002).

There is little information on the inner 100 au region, as it is masked in imaging at short wavelengths, though mid-IR images confirm that there is dust in the inner regions (Fisher et al. 2000; Maaskant et al. 2014). In the outer disk, scattered light imaging (Clampin et al. 2003) shows two belts of emission between 175 and 400 au, with a gap between 215 and 300 au and several spiral features. While the open spirals at > 400 au may be caused by a flyby of a known stellar companion at 1000 au projected separation (Quillen et al. 2005; Ardila et al. 2005), the more tightly wound ones at 200 and 325 au are best explained by internal perturbations from a (yet unseen) planet embedded in the disk (Wyatt 2005).

2.2 Young (8-20 Myr) A star debris disk sample

The circumstellar environments of main sequence A stars evolve on timescales of ~ 150 Myr (Rieke et al. 2005), and perhaps even faster (Currie et al. 2008). Thus to capture the structure of debris disks in the immediate aftermath of the dispersal of the protoplanetary disk we need to consider the youngest known debris disks. To construct an unbiased sample we use the nearby ~ 20 Myr β Pic moving group (BPMG; Zuckerman et al. 2001; Binks and Jeffries 2014; Mamajek and Bell 2014) and the 8 Myr TWHya association (TWA; Ducourant et al. 2014). These associations contain 6 main sequence A stars of which 4 are known to host debris disks, the properties of which are summarised in Table 1 and discussed in greater depth below.

HR4796A: The debris ring in this system has been imaged both in mid-IR and scattered light and found to lie in a narrow ring at 80 au in radius, with both a brightness asymmetry and offset ring centre implying that the ring is eccentric (Moerchen et al. 2011; Thalmann et al. 2011; Wahhaj et al. 2014; Perrin et al. 2014). The presence of hot dust is debated (Wahhaj et al. 2005; Riviere-Marichalar et al. 2013; Chen et al. 2014; Kennedy and Wyatt 2014). No CO was detected suggesting an upper limit of $7 M_\oplus$ on the mass of molecular H_2 gas present (Zuckerman et al. 1995; Greaves et al. 2000), with more recent upper limits on OI from Herschel (Meeus et al. 2012).

β **Pic**: Scattered light from this edge-on debris disk is seen out to 1000s of au (Smith and Terrile 1984), but the planetesimals creating the dust are concentrated between 60-130 au (Augereau et al. 2001; Dent et al. 2014). The structure of the disk includes many asymmetries including a warp at 80 au which is at a similar spatial scale to a clump seen in both μm-sized dust and CO (Telesco et al. 2005; Dent et al. 2014). The inner regions of the system are not completely empty, hosting both a giant planet orbiting at 9 au (Lagrange et al. 2010), hot dust seen in the emission spectrum inferred to lie at a comparable distance (e.g., Okamoto et al. 2004), as well as transient absorption features along the line-of-sight to the star inferred to originate in distintegrating planetesimals (so-called Falling Evaporating Bodies, or FEBs; Vidal-Madjar et al. 1994). Resolved imaging of metallic ions (Brandeker et al. 2004; Nilsson et al. 2012) and of the CO emission (Dent et al. 2014) shows the spatial distribution of gas in this system, further constraints on which are found from far-IR CII lines (Cataldi et al. 2014). The gas is located in the outer disk and is thought to originate in the planetesimals.

HD172555: Hot dust was detected in the mid-IR spectrum of this star from which the composition of the dust could also be determined (Chen et al. 2006; Lisse et al. 2009). This hot emission was marginally resolved placing it between 1-8 au (Moerchen et al. 2010; Smith et al. 2012). The absence of far-IR emission above that expected from the hot dust suggests there is no cold dust in this system (Riviere-Marichalar et al. 2014). The presence of SiO gas was suggested from the mid-IR spectrum (Lisse et al. 2009; Johnson et al. 2012), and OI emission was detected in the far-IR implying a mass of gaseous oxygen $> 10^{-4} M_\oplus$ (Riviere-Marichalar et al. 2012); variable CaII absorption features along the line-of-sight to the star also suggest the presence of FEBs (Kiefer et al. 2014). Another example of a young hot dust-only A star is ~ 10 Myr-old A9V EF Cha (Rhee et al. 2007).

η **Tel**: The debris disk of this system was resolved in the mid-IR at a radius of 24 au, but it was shown that there is an additional unresolved component at 4 au (Smith et al. 2009). The fractional luminosities of the two components determined from a two temperature fit to the SED show these are of comparable luminosity. Gaseous CII (but no OI) was found in the far-IR spectrum giving a mass of gaseous carbon of $> 1.6 \times 10^{-4} M_\oplus$ (Riviere-Marichalar et al. 2014). The star has an M7/8V binary companion at 192 au projected separation (Lowrance et al. 2000). Other young A stars with CII but no OI include 40 Myr-old 49 Ceti (Zuckerman and Song 2012; Roberge et al. 2013) and 30 Myr-old HD32297 (Donaldson et al. 2013). Also notable are ~ 10 Myr-old A stars HD131488 and HD121191 that both have two component disks (Melis et al. 2013).

With such small numbers there is no guarantee that the outcomes in the above sample are representative. Furthermore, stars in this sample are all members of nearby moving groups, rather than say members of larger clusters or stars formed in isolation, which is another reason that they may not represent an unbiased sample of the progenitors of older main sequence

Table 1 Properties of the four A stars from the TWA and BPMG with debris disks

Star	Hot Dust	Cold Dust	Gas
HR4796A (A0V, 8 Myr, 67 pc)	No?	Narrow ring 80 au $f = 5 \times 10^{-3}$	No
β Pic (A5V, 20 Myr, 19 pc)	~ 10 au $f = 0.9 \times 10^{-3}$	Broad ring 60-130 au $f = 1.5 \times 10^{-3}$	CO (+...)
η Tel (A0V, 20 Myr, 48 pc)	4 au $f = 1.6 \times 10^{-4}$	24 au $f = 1.4 \times 10^{-4}$	CII
HD172555 (A5V, 20 Myr, 29 pc)	1-8 au $f = 0.7 \times 10^{-4}$	None detected	OI

A stars. Nevertheless, the above sample gives a sense of the diversity in location, width and composition of young debris disks, as well as the fraction of HAe disks that might end up in different outcomes. Another young disk close to this age, but not part of the unbiased sample, that we will also use to highlight one aspect of the evolution is HD21997.

HD21997: This A3IV/V member of the 30 Myr Columba association rose to prominence because of the high fractional luminosity of its debris disk ($f = 5 \times 10^{-4}$; Moór et al. 2006), and the subsequent detection of CO (Moór et al. 2011) and imaging of its disk with ALMA (Moór et al. 2013; Kóspál et al. 2013). Another main sequence A star of comparable age with CO is 40 Myr-old 49 Ceti (Dent et al. 2005; Hughes et al. 2008).

2.3 Observational classification

As mentioned above, there is no accepted observational definition of a debris disk. For some authors the distinction lies in the total fractional luminosity (the ratio of the infrared luminosity to that of the star, $f = L_{\mathrm{IR}}/L_\star$), since this approaches 1 for the brightest HAe disks (e.g., $f \approx 0.5$ for HD100546), with slightly lower values $f < 0.25$ for group II HAe disks (Kenyon and Hartmann 1987), and the HAe stars closest to the transition towards debris disks have $f \approx 0.01$ (e.g., $f = 0.01$ for HD141569 and $f = 0.03$ for 51 Oph). Thus the dividing line is usually placed at $f \approx 0.01$, which is around the level at which the dust might be expected to become optically thin in the radial direction to the starlight (i.e., in the optical and UV). However, the transition from optically thin to optically thick depends on the degree of settling in the disk, and it may be possible to make a protoplanetary disk model with a lower fractional luminosity as long as it has a low dust scale height. It may, however, be hard to maintain such a low height for small dust if it is entrained in the gas which inevitably has a vertically broad distribution due to its pressure support. It is also possible to make a debris disk model with a higher level of fractional luminosity, since the disruption of a single large asteroid, if in close proximity to the star, can release sufficient cross-sectional area to intercept a large fraction of the starlight. These issues were discussed in Kennedy et al. (2014) in relation to the disk of HD166191 for which different interpretations are invoked by different authors, highlighting the difficulty of coming up with an independent classification scheme.

Since the majority of both debris and protoplanetary disks are identified in mid-IR and far-IR surveys it would be helpful if a classification scheme could be devised based on those surveys, for example, based on the fractional excess R_λ (the ratio of total flux from a system to that from the star) at an appropriate wavelength λ in the range $5 - 500$ μm. In Fig. 1 we show the fractional excess at 12, 22 and 70 μm, both for the individual objects discussed in §2.1 and §2.2, and for A stars with a much wider range of ages. At young ages this sample comprises relatively nearby HAe stars from the literature and more distant A-stars in young clusters from Hernández et al. (2005). HAe stars have been the subject of numerous observational studies since their first identification as a group by Herbig (1960), and subsequent studies of Thé et al. (1994), Sylvester et al. (1996), van den Ancker et al. (1998), Sylvester and Mannings (2000), Malfait et al. (1998) revised the membership list to eventually include not only the stars associated with a known star-forming region, but also stars in isolation (see §2.1). We compiled a sample of A-type stars from these works, and for which ages have been determined. Older stars were taken from Su et al. (2006) and the DEBRIS and SONS surveys (Matthews et al. 2010; Panić et al. 2013). We also included sources with B9 spectral type designation, given that these are often characterised as A0 or B9/A0 stars. We do not claim the plotted star sample to be free from bias, since it simply comprises those in the literature, however it does plot both protoplanetary and debris disks in a consistent manner to facilitate comparison of these populations.

Fig. 1 shows that at all wavelengths there is a clear downward trend of excess with age. In particular the absence of large excesses at ages $\gg 10$ Myr is real, since many stars were observed for which such excesses would have been readily detectable. It is less clear whether the absence of low excesses at ages < 10 Myr is real, because there is a bias in that young stars are less abundant and so are usually found at greater distance, which means that deeper observations are required to measure the levels of fractional excess that are more common around

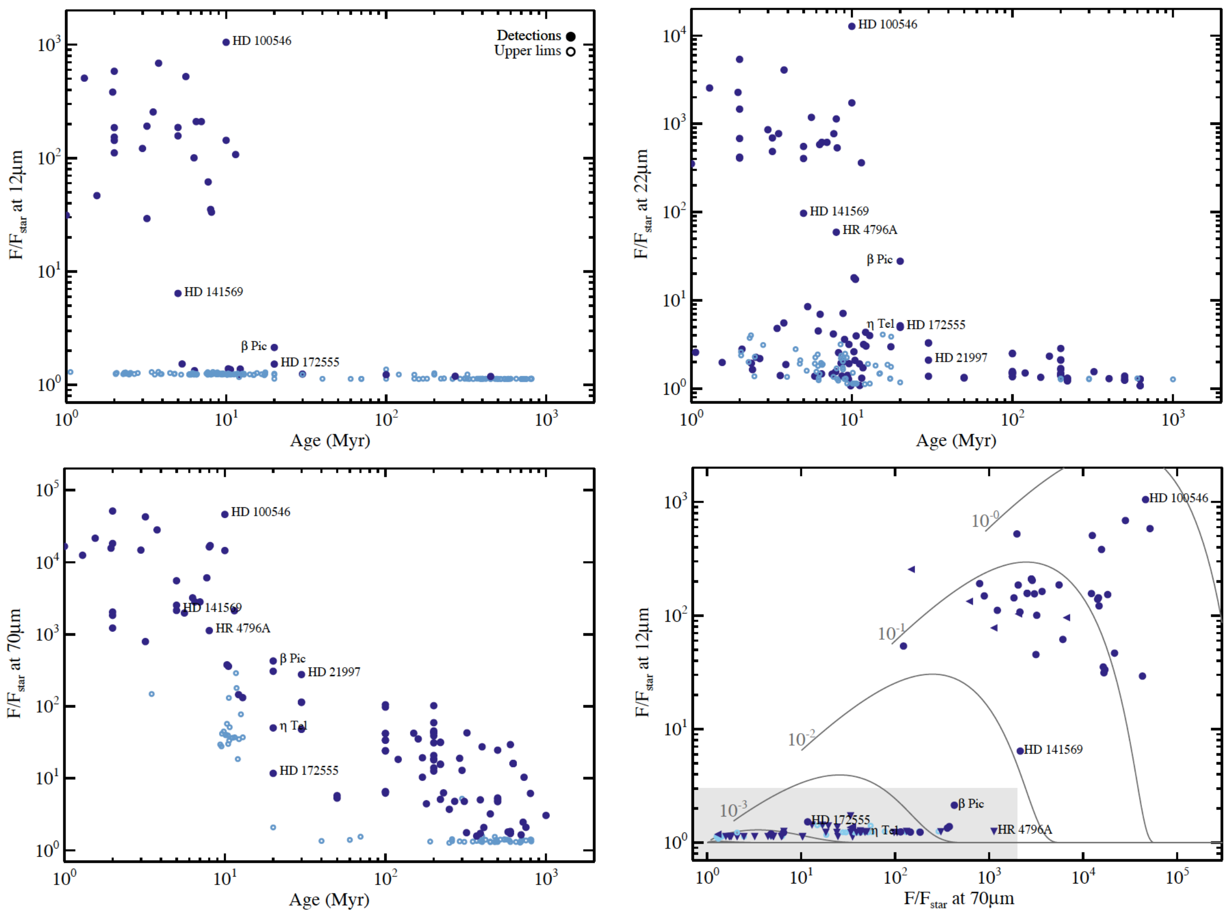

Fig. 1 The ratio of observed to stellar fluxes, i.e. the fractional excess R_λ where 1 represents detection of the photosphere, of A stars as a function of age: **(Top left)** and **(Top right)** – 12 and 22 μm excesses from WISE, **(Bottom left)** – 70 μm excesses from Spitzer and Herschel. For all stars the photospheric level at these wavelengths was estimated from a photosphere model fit to shorter wavelength data. Filled blue circles are detections; open light blue circles are upper limits. HR4796A, η Tel and HD21997 are upper limits in the top left panel. The **(Bottom right)** panel shows 12 μm versus 70 μm excess on which the grey shaded region summarises the empirical classification proposed for the boundary between protoplanetary and debris disk; triangles are upper limits at just one wavelength (left-pointing for upper limits at 70 μm and down-pointing for limits at 24 μm). The grey lines show the fractional luminosity implied if the spectrum is assumed to be a single temperature black body that matches the excesses at these two wavelengths.

older stars. Observations of nearby main sequence stars typically reach the calibration limit below which it is not possible to discern an excess photometrically (which is at R_λ of around 1.10), whereas those of the more distant younger stars are often limited by the length of integration or by the background confusion level, in particular at 70 μm (see also Carpenter et al. 2009).

There is an additional complication in that samples of young A stars are biased toward having large excesses, because such stars are identified by their emission lines and their interpretation confirmed by virtue of their excess infrared emission. That is, it is not possible to tell from this plot whether large excesses are a majority or a minority in this age range because it is a biased sample. This bias can be addressed by observing all A stars in given star forming regions to determine the distribution of excesses. Such studies performed at near-IR wavelengths suggest that a significant fraction of 5-10 Myr A stars should have already lost their protoplanetary disks (Hernández et al. 2005). We included stars from Hernández et al. (2005) in Fig. 1, which confirms that a large fraction of these young stars have observational characteristics similar to older debris disks, and suggests a bimodal distribution of excesses at young ages. However, we also note that small number statistics and potential environment dependent biases remain an issue, and of course the plot still includes the biased HAe populations.

The clearest observational distinction between what we call a protoplanetary disk and what we call a debris disk is at 12 μm (Fig. 1, upper left). The dividing line at this wavelength is at $R_{12} = 3$, which is slightly below HD141569 which has been called both (but is a protoplanetary disk with this definition). To avoid the possibility of identifying an old system in which a single asteroid collided in the inner regions with a protoplanetary disk, we impose a further requirement of $R_{70} < 2000$ to identify a system as having a debris disk. This classification scheme is summarised in the bottom right panel of Fig. 1, where it is worth reminding the reader that this empirical classification scheme is derived based on a sample of A stars, and so cannot necessarily be applied to other spectral types. The lines of constant fractional luminosity on that plot (under the assumption that the spectrum resembles a single black body) show that this classification results in a boundary at a fractional luminosity between 10^{-3} and 10^{-2}. One question that remains is whether this classification scheme would misidentify transition disks with very clean inner gaps as debris disks. While we are not aware of any such systems, these may be absent from the HAe class, because of the fact that classification as a HAe star initially relied on a near-infrared excess (among other things) as an important indicator of their youth (Thé et al. 1994). Indeed such systems do exist around around young lower mass stars (e.g., PZ99; Mathews et al. 2012; Zhang et al. 2014).

Note that in §2.4 we will conclude that gas density is the most important physical distinction between the two classes of object, but the difficulty of detecting this component, and the large uncertainties involved in deriving a mass from the observations (Miotello et al. 2014), mean that we are essentially using the dust thermal emission as a diagnostic of the presence of gas. In this respect it should be pointed out that any classification scheme that relies only on the dust emission spectrum must be fallible if there is a regime for which the SEDs of protoplanetary and debris disks are indistinguishable.

2.4 Physical distinction

Any observational classification for the debris disk – protoplanetary disk boundary should also consider the physical difference between the two types of object. The physical distinction that is usually invoked in the literature is that the dust in debris disks is short-lived and so must be secondary in nature (i.e., continually replenished in the break-up of larger objects, Backman and Paresce 1993). A short dust lifetime can be inferred if the dust is determined to be small (microns in size) either from the thermal emission (e.g., from its temperature if its radial location is known, or from mid-IR spectral features or the sub-mm slope), or from the inferred scattering properties of the dust. Poynting-Robertson drag removes such small dust on Myr timescales that are much shorter than the age of the star precluding the possibility that the dust is primordial.

Such small, and likely secondary, dust also exists in protoplanetary disks, however the young age of their host stars complicates the timescale arguments. Radiation forces are also reduced by the high optical depth of protoplanetary disks, meaning that only a negligible fraction of dust is directly exposed to stellar light in the surface layer. Rather the dust evolution is dominated by growth in collisions that is concurrent with (and aided by) the dust sinking toward the midplane due to gravity, and so to deeper and denser layers where the starlight is not able to penetrate.

While the above reasoning suggests that small dust in protoplanetary disks can be primordial, in fact this is unlikely for the bulk of the dust inside the optically thick region of the disk, and especially the disk midplane. There the high dust densities result in frequent collisions, and in these collisions the dust is expected to grow into larger pebbles (Takeuchi and Lin 2005; Testi et al. 2014). Indeed observational evidence for grain growth has been found in a number of sources, starting with mid-IR observations (Bouwman et al. 2001; van Boekel et al. 2003), and then longer wavelength observations showing that millimetre dust is abundant in the outer disks (Testi et al. 2003; Natta et al. 2004; Wilner et al. 2005; Andrews and Williams 2007b). Since collisions are expected to remove the micron-sized dust on short timescales (through grain growth), and interactions with gas would also remove the pebbles on short timescales, the continued presence of both components throughout the protoplanetary disk phase implies that collisions result in dust destruction as well as growth (Dullemond and Dominik 2005), and this is expected given the range of dust sizes and relative velocities anticipated in the disk (Brauer et al. 2007). Therefore, there is strong evidence that the bulk of the small dust we see in protoplanetary disks is secondary in nature (i.e., it must be continually replenished from the destruction of larger grains), just as it is in debris disks.

If the size distribution in a protoplanetary disk is a quasi-steady state in which growth and destruction at each size are balanced (Windmark et al. 2012; Garaud et al. 2013), then the main physical difference with a debris disk could be that in the latter the collisional velocities are much higher so that dust growth is no longer possible. Furthermore it is tempting to identify the presence of gas with that distinction, because gas damps collision velocities of the small dust (and big planetesimals) in protoplanetary disks. However, recent models have considered the possibility that a debris disk started with a low level of stirring could persist for Gyr at detectable levels even in the absence of gas (Heng and Tremaine 2010; Krivov et al. 2013). Indeed the observable properties predicted for unstirred disks (i.e., a spectrum and resolved radius compatible with black body grains) match those of the cold debris disks discovered by Herschel (Eiroa et al. 2013; Krijt and Kama 2014), though the existence of this latter population is debated (Gáspár and Rieke 2014). The sharp outer edge of the HR4796A debris ring in scattered light has also been attributed to a low level of stirring (i.e., low collision velocities; Thébault and Wu 2008).

Such unstirred debris disks share many features in common with protoplanetary disks, since neither require the presence of objects larger than the cm-sized pebbles required to explain the mm-wavelength observations, though the unstirred debris disks go further to imply an absence of planets (which would otherwise stir them, unless the planets are on perfectly circular orbits) which is not the case for protoplanetary disks. In constrast, planetesimals are required in conventional debris disks to replenish the small short-lived dust, the presence of which distinguishes them from their unstirred counterparts, over main sequence lifetimes. It is also likely that the stirring of planetesimals in debris disks is somehow caused by the growth of planet-sized objects in their systems, either through the gravitational perturbations of embedded Pluto-sized objects (Kenyon and Bromley 2010) or the secular perturbations of fully formed planets which need not lie close to the disk in semimajor axis (Mustill and Wyatt 2009). Indeed a warp at 80 au in the β Pic debris disk provides evidence that it is being stirred by a $9M_{\rm Jup}$ planet seen to be orbiting at 9 au (Augereau et al. 2001; Lagrange et al. 2010), and spiral structure in the HD141569 disk (Clampin et al. 2003) may have a similar implication (Wyatt 2005). However, planets are not required in debris disks since planetesimals could simply be born on orbits with high collision velocities (e.g., Walmswell et al. 2013), or achieve them as a natural outcome of disk evolution (e.g., due to asymmetric mass-loss; Jackson 2014), as damping timescales can be longer than gas dispersal timescales for large enough planetesimals.

Clearly the level of stirring that planetesimals receive and their radial distribution depend on the architecture (and indeed existence) of the planetary system within which they reside. An important question then is when systems of (putative) planets and planetesimals achieve the structures seen around main sequence stars. The ages of CAIs (Calcium-aluminium-rich inclusions) and meteorites in the Solar System imply that formation of planetesimals (at least in the inner Solar System) occurred early on in the protosolar nebula (Shukolyukov and Lugmair 2003) and over an extended period of > 1 Myr (Wadhwa et al. 2005; Cuzzi et al. 2008), though whether those planetesimals were born with sizes of 100s of m or 100s of km remains debated (Morbidelli et al. 2009; Kobayashi and Löhne 2014). It also seems likely that the formation of planetary embryos (if they form at all) precedes the transition disk phase, since it makes more sense for these objects to form in the long period when sufficient mass was available, rather than during the short transition phase during which that mass was depleted. Moreover there is some observational evidence for planets or companions in transition disks (Huélamo et al. 2011; Kraus and Ireland 2012; Quanz et al. 2013; Biller et al. 2014; Reggiani et al. 2014), and the gas giant planets seen around many main sequence stars must have formed in the presence of significant quantities of gas.

Hence a useful hypothesis to test is that the planetary system and its planetesimal belts are already largely in place before the transition disk phase. This does not rule out that the planets continue to grow at later phases through collisions, or that they migrate in the gas-rich protoplanetary disk phase (Walsh et al. 2011), and neither does it preclude the possibility of a period of dynamical restructuring following the dispersal of the protoplanetary disk (Gomes et al. 2005; Raymond et al. 2012). Such system changes would simply weaken the extent to which this hypothesis is true. If these changes commonly render systems unrecognisable between their protoplanetary and debris phase architectures then the hypothesis is no longer useful, and this would be the case if for example these structures were only formed during disk dispersal (see §3.2; e.g., Alexander and Armitage 2007). As long as this is not the case, we should be looking to debris disks to tell us about the distribution of the less observable components of protoplanetary disks (i.e., the planets and planetesimals that are embedded in a much brighter disk of gas and dust). Furthermore, this hypothesis allows us to propose a clear physical distinction between protoplanetary and debris disks, which is that protoplanetary disks contain a large quantity of primordial gas which is also suffused with small dust grains, made up of the dust which did not yet grow to planetesimal sizes, as well as dust released in planetesimal collisions which is then radially mixed through entrainment in the gas. It then makes sense to peg the level of gas at which the transition is defined as that which is sufficient to dominate the motion of the dust, since that may be empirically determined from its effect on the observational properties of the dust disk, and so provides some justification for basing the observational distinction given in §2.3 on observations of the dust rather than the gas.

3 Five stages in the transition

Given that we witness individual disks at just one evolutionary stage and only have incomplete information about each of them, and moreover stellar age is not a reliable measure of the degree to which an individual disk has evolved, it is always going to be difficult to make firm conclusions about the evolution through the transition from the protoplanetary to debris stage. This is compounded by the rapidity of the transition which leaves us with few objects that are truly caught in transition. The following discussion is thus somewhat speculative, but is based on what can be learnt from looking at disks as close to the transition as possible and noting the quantity of different components that are present. We have identified five key stages in the evolution, represented by the young disks discussed in §2.1 and §2.2. However, we are not claiming that any of

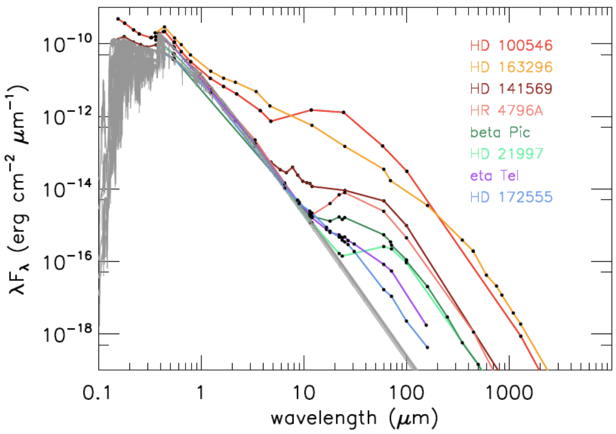

Fig. 2 Spectral energy distributions of A star disks selected for the similar luminosities and effective temperatures of their host stars. All emission spectra have been scaled to 100 pc so that the photospheric emission for all should be similar to that of HR4796A which is shown in grey. Broad band photometry for each star is shown with black dots without error bars for clarity. The spectra obtained by joining these photometric points illustrate the evolution from transition disk (HD100546) to one depleted in mm-sized grains (HD141569) to one in which the inner regions have been cleared and the remaining planetesimals are left in a narrow ring (HR4796A). Alternative outcomes (or the descendants of such rings) include β Pic and HD21997 which have only slightly lower cold dust levels, while η Tel and HD172555 represent outcomes in which cold dust is more depleted but (relatively) small quantities of dust exist in the inner regions which may be a transient phenomenon.

these disks will evolve into systems that resemble each other, and neither do we claim that the order of the evolution is uniquely determined; indeed these stages may take place concurrently rather than consecutively, similar to the homologous depletion proposed for protoplanetary disks (Currie et al. 2009). Rather we expect the evolution to be inherently chaotic, presumably determined by how planet formation and disk dispersal processes play out in each system (see §2.4). Nevertheless, the subdivision of the evolutionary stages in this way provides a framework for discussion from which to make progress in our understanding of the transition.

We start in §3.1 with the transition disk stage illustrated by HD100546. This is followed in §3.2 by the depletion of mm-sized dust in the outer disk illustrated by HD141569, and a discussion of the removal of the dust in the inner regions in §3.3 the continued existence of which is illustrated by HD172555 and η Tel. The removal of the gas is discussed in §3.4 using the examples of β Pic and HD21997, and finally the ring-like concentration of planetesimals illustrated by HR4796A is discussed in §3.5. The SEDs of a few of these objects are shown in Fig. 2, which illustrates this transition, and is similar to figure 8 of Kennedy et al. (2014) which shows the evolution of the circumstellar disks of Sun-like stars.

3.1 Transition disk

The presence of inner holes in transition disks has a profound effect on their near infrared spectrum and their inner disk structure revealed in high resolution imaging, but otherwise transition disks are not significantly different to full disks in terms of their far infrared luminosity (Rodgers-Lee et al. 2014). While this class may correspond to the low end of the protoplanetary disk dust mass distribution (Owen and Clarke 2012), a significant number of massive transition disks also exist (such as HD100546). However, transition disks may have larger dust grains than full disks (Pinilla et al. 2014), as well as lower levels of OI gas which could indicate that they are less flared (Keane et al. 2014), suggesting they may be more evolved.

The fraction of HAe disks that are classed as transition disks is poorly known for the reasons described in §2.1. However, the fraction of the protoplanetary disks found around lower mass stars that are classed as transition disks ranges from 10-20% (e.g., Muzerolle et al. 2010; Furlan et al. 2011). If the same fraction applies to HAe disks one implication is that, since the remaining 80-90% of full disks in these regions may also pass through a transition disk phase, the fact that only a few percent of stars are found to have giant planets at large distances (e.g., Biller et al. 2013) suggests that planet-induced clearing is unlikely to explain all transition disks unless the planets required to do the clearing can be below the detection threshold of the imaging surveys (a few $M_{\rm Jup}$).

On the other hand planets (or indeed multiple planets) provide a mechanism to carve a hole while maintaining accretion at levels observed toward some transition disks (Williams and Cieza 2011; Dodson-Robinson and Salyk 2011; Zhu et al. 2012), and a planet does not necessarily have to be massive to open a gap (Baruteau and Papaloizou 2013). Furthermore, in some transition disks a lop-sided asymmetry in millimetre dust has been found (van der Marel et al. 2013; Casassus et al. 2013), providing indirect evidence for trapping of millimetre dust in planet-induced pressure waves (Pinilla et al. 2013). The alternative mechanism invoked to explain the inner clearing is photoevaporation, which is indeed expected to result in disk holes (e.g., Alexander and Armitage 2007), although this is a less viable explanation for the most massive transition disks, since this mechanism operates once disk mass is already depleted (Owen and Clarke 2012), and also has problems explaining the accreting transition disks (e.g., Cieza et al. 2010). A realistic picture probably includes both processes; e.g., clearing by planets very close to the star could trigger efficient photoevaporation such that transition disks do not necessarily have planets close to the outer edge of the hole or gap.

Considering that the inner few tens of au of most debris disks are also devoid of material, it is tempting to look at transitional disks as one of the steps towards debris disk formation. However, the strong coupling of the dust in transition disks to the distribution of gas (which is no longer present at later phases) means that there is no guarantee that the dust in transition disks traces the distribution of planetesimals. Indeed, it is possible that any signatures of the hole that existed in the transition disk and its location may be erased once the gas disperses.

3.2 Depletion of millimetre-sized dust in the outer disk

As illustrated in Fig. 2 the most easily detected observational difference between protoplanetary and debris disks is the excess emission at a range of wavelengths, from infrared to the millimetre. In this section, we focus on the evolution of the largest observable dust particles traced by millimetre-wavelength observations. Millimetre emission arises predominantly from dust a few hundred microns to a few centimetres in size, and is often used as a dust mass tracer because it is optically thin, contrary to the case of shorter wavelengths.[2] Evidence of grain growth to millimetre sizes exists even at the early stages of protoplanetary disk formation, and arguably this is the size range at which the majority of the solid mass in a protoplanetary disk resides throughout its evolution (though a large mass in smaller and larger grains can be hidden by optical depth and opacity effects, respectively). The conclusions reached about the evolution of the population of millimetre grains may broadly apply to that of the population of smaller grains, since these are linked to some extent through the size distribution (see §2.4), with the caveat that the different forces acting on dust of different sizes through its interaction with gas and stellar radiation adds complexity to such inferences that will not be discussed here.

The evolution of dust mass around nearby stars is shown in Fig. 3 (Panić et al. 2013). While the interpretation of this plot is complicated without a detailed

[2]Here optical depth refers to that along the line-of-sight to the observer at the wavelength in question. In the optically thin regime the observer sees all of the emission from the disk at this wavelength, whereas much of that emission remains hidden in the optically thick regime.

treatment of the non-detections (for a consideration of this for protoplanetary disks around lower mass stars see Andrews and Williams 2007a), it is clear that there is a neat division at $\sim 10\,$Myr between younger (protoplanetary) disks for which there is $> 1M_\oplus$ of dust, and older (debris) disks having $< 1M_\oplus$ of dust; old stars with $> 1M_\oplus$ of dust would have been readily detectable so their absence is independent of considerations of the non-detections that are not included on this figure. The fact that the transition disk of HD100546 lies firmly in the protoplanetary disk mass range is part of the reason that §3.1 stated that such systems have not progressed very far along the evolutionary track to losing their protoplanetary disks.

While it is not possible to generalise into a sequence from individual objects, and we should reiterate the caveat that the order and consecutive nature of the stages is uncertain, the loss of the mm-sized grains as the next stage in the process is guided by HD141569, a 5 Myr HAe star which has all the characteristics of a protoplanetary disk (10^{-4} $M_\odot$ of gas, PAH emission, spatially extended scattered light features), but has a dust mass of $0.7M_\oplus$ that is significantly depleted compared with other protoplanetary disks (see §2.1). The depletion of mm-sized grains likely occurs quickly given the lack of evidence for evolution in their mass during the protoplanetary disk phase (e.g., Carpenter et al. 2014), though deeper mm-wavelength observations would help to constrain the evolution in this phase.

The fate of millimetre-sized dust grains in protoplanetary disks is uncertain. One possibility is that the concentration of such material into radially narrow features following the carving of an inner hole in the transition disk (van der Marel et al. 2013) results in high enough densities for gravitational collapse or streaming instabilities and the direct formation of planetesimals (Chiang and Youdin 2010; Johansen et al. 2014). A similar fate is suggested by models in which the gas in protoplanetary disks is dispersed from the inside out from photoevaporation by stellar UV and X-ray radiation (Clarke et al. 2001), since dust in such models gets pushed out with the photoevaporation front which sweeps up the dust (Alexander and Armitage 2007). However, neither of these models can follow the evolution of the dust up to the formation of planetesimals, because their assumptions break down once dust densities exceed gas densities. Thus it is also possible that these grains decouple from the gas before they have had a chance to grow into planetesimals and perhaps are deposited as a ring of debris at the location where this occurs. Such debris rings could then be depleted by rapid collisional erosion if they have also been excited to high enough collision velocity by this stage.

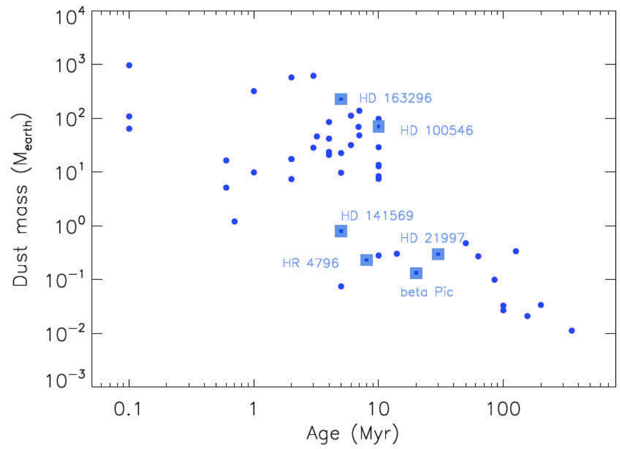

Fig. 3 Mass in millimetre-sized dust grains inferred from sub-mm observations as a function of stellar age for A and B-type stars, adapted from Panić et al. (2013), including also masses from Sandell et al. (2011) and Thi et al. (2013). Uncertainties in dust opacity dominate the uncertainties in the mass estimates, which could be up to 10 times higher or 2 times lower. Absolute ages are only known to within a factor of a few, though relative ages within the sample should be more accurate.

A more general consideration of this problem shows that there are just two outcomes for the mm-sized grains (recalling that these likely comprise a significant fraction of the solid mass of a protoplanetary disk). Since they cannot be dragged away by a photoevaporative wind, and P-R drag takes many 10s of Myr to deplete mm-sized dust from 10s of au, their loss can only be through collisions.[3] If those collisions are predominantly destructive then their mass will end up in much smaller dust grains that can be removed by various mechanisms, such as radiation pressure blow-out or coupling to the photoevaporative flow. The alternative is for the mass originally in mm-sized dust to end up (through collisions) in large objects, either through their growth into planetesimals, or through their accretion onto already formed planetesimals or planets. The continued presence of gas after the depletion of the mm-sized dust in HD141569 seems to argue against loss by collisional erosion, since that gas would damp collision velocities and favour grain growth. However, since we do not know yet exactly where the mm-sized dust lies in relation to the gas in HD141569 (e.g., other transition disks with low millimetre fluxes have been found to arise from systems with small outer disk radii; Piétu

[3]The mm-sized dust can also be accreted onto the star through drag induced by the gas, but since this process would also occur throughout the earlier protoplanetary disk phase, relative to which the transition is rapid, this likely only affects a small fraction of the dust.

et al. 2014), it may be that these two components are sufficiently disconnected for collisional erosion to be viable, a possibility that will be probed with millimetre interferometric observations (Flaherty et al., in prep.).

The growth of the mm-sized dust into planetesimals on the other hand makes sense if one was to believe that solid mass is conserved between the protoplanetary and debris disk phases (as is the assumption for example in the minimum mass solar nebula model). While the dust mass has undeniably been depleted by the debris disk phase (see Fig. 3), this must be the tip of the iceberg, since if all of the observed solid mass was all there was, then it would be collisionally depleted on Myr timescales. The presence of debris disks at 100s of Myr ages thus implies the existence of planetesimals of at least km in size that are feeding the observed dust (Wyatt and Dent 2002). This leads to inferred masses of 10s of $M_\oplus$ of solid material in the debris disks that are comparable with those present in protoplanetary disks.

We do not favour either scenario here, but point out that the fate of mm-sized dust has significant implications for our interpretation of young debris disks. For example, if the mm-sized dust (which is seen to persist into the transition disk phase, §3.1) grows into planetesimals then the debris disk architecture is not already in place during the protoplanetary disk phase, invalidating the hypothesis proposed in §2.4. Conversely if the mm-sized dust grains are collisionally depleted then the young bright debris disks (like HR4796A) could be an ephemeral phenomenon associated with the erosion of this population, which is superimposed on a longer term (fainter) evolution of any pre-existing planetesimal belts. Either way, this emphasises that there are two potential sources for dust in debris disks: pre-existing planetesimals, and the destruction of whatever structure the mass in mm-sized dust got shaped into during disk dispersal. It will be hard to discern these sources observationally.

3.3 Evolution of hot dust in inner regions

Hot dust in the inner regions of protoplanetary disks is a natural consequence of models in which the dust is well mixed with the gas. Even if the dust which started in the inner few au has long since grown into planetesimals or planets, or been accreted onto the star, this region is continually repopulated by dust which started off further out but then migrated in either through gas drag or simply with the bulk motion of the gas. Here we point out that another source for hot dust in protoplanetary disks is in debris-like processes (i.e., in processes more commonly associated with debris disks, as opposed to the dust growth and drift processes considered to dominate in a protoplanetary disk). This may particularly be the case in systems like HD100546 where we know the hole is devoid of gas (both H_2 and CO), but contains hot dust at < 0.7 au. Such *pre-transition disk* systems are often considered to arise at the onset of photoevaporation which carves an annular gap at 10s of au, whereupon the inner disk drains onto the star (Clarke et al. 2001). However, it is worth considering whether this dust is second generation, formed from collisions of larger bodies which may also have been present earlier on. Here we focus on the explanations that have been proposed for the origin of hot dust seen in debris disks, noting that it may be productive to consider whether these mechanisms are also operating at earlier phases (e.g., Kennedy et al. 2014).

Three of the six 8-20 Myr A stars have hot dust. In the case of HD172555 it only has hot dust, at a temperature that puts it at a few au, a location confirmed with mid-IR imaging and interferometry (Smith et al. 2012). For η Tel there are two dust components, one at 24 au that is resolved in mid-IR imaging (Smith et al. 2009), and another at a few au that is unresolved in those images and also inferred from the spectrum. The question for these hot components is: are these asteroid belt analogues, sublimation of comets scattered in from outer regions, or evidence for the ongoing formation of terrestrial planets or super-Earths?

A growing number of two temperature disks found around older (100s of Myr) stars (Morales et al. 2011; Su et al. 2013; Chen et al. 2014), i.e., systems with both cold and hot dust like η Tel, gives an indication that the hot dust in some of these systems may have a cometary origin (Kennedy and Wyatt 2014), since the outer belts provide an appropriately long-lived source population. A rather contrived set of planetary system properties would be needed to result in detectable hot dust from an outer planetesimal belt that lies below the detection threshold (Bonsor et al. 2012), and so this is unlikely to be the origin of hot dust-only systems like HD172555. However, this is a reasonable proposition for young systems with hot and cold dust, particularly if the early phase in the system's evolution is characterised by dynamical settling and so intense cometary activity (Bonsor et al. 2013a). Indeed it has been proposed that transient spectral absorption events in some transition disks including HD100546 is caused by Falling Evaporating Body (FEB)-like cometary activity (Beust et al. 2001).

High levels of hot dust is almost exclusively a phenomenon of young ($\ll 100$ Myr) stars (see Fig. 1; Melis et al. 2013; Kennedy and Wyatt 2013). This is consistent with both an asteroid belt and a planet formation interpretation, since rapid collisional depletion at such proximity to the star means that asteroid belts quickly evolve below the detection threshold (Wyatt et al. 2007b) and rapid collisional evolution is also the explanation for the eventual cessation of planet formation processes. The formation of terrestrial planets or super-Earths is an attractive proposition for the origin of the hot dust because models of such processes that are successful at reproducing the Solar System's terrestrial planets predict that hot dust should be readily detectable at this epoch. Such models start out with km-sized planetesimals which grow through collisions into embryos, and later the number of embryos is whittled down as they coalesce into a small number of roughly Earth-mass planets. Planetesimal collisions would be expected to produce dust, the level of which is predicted to be at an easily detectable level up to several 10s of Myr (Kenyon and Bromley 2005). Since such models do not include the debris created in giant impacts between the embryos, the aftermath of which should also be detectable for $\sim 15\,$Myr (Jackson and Wyatt 2012), it is clear that if planet formation in this manner (whether the outcome is 1 or 10 Earth mass planets) is ongoing after or indeed during the protoplanetary disk phase, then it should be detectable. There may be evidence from the mid-IR spectrum to support this for HD172555, since a sharp feature at 11 μm is attributed to silica that is expected to be produced in high velocity collisions such as those between planetary embryos (Lisse et al. 2009; Johnson et al. 2012).

Given the plethora of opportunities for creating dust in the inner regions of these systems it is not a surprise that it is detected around many young main sequence A stars. It would only be absent if the inner regions were completely empty of planetesimals, any rocky planets present were already sufficiently separated for further collisions amongst them to be unlikely, and the outer planetary system was arranged so as to prevent planetesimals from any outer planetesimal belt being scattered into the inner regions. Moreover, unless the formation of asteroid belts or terrestrial planets occurs during the transition, these objects must be present during the protoplanetary disk phase (including the transition disk phase). As such it is important to question how much of the hot dust in protoplanetary disks of all varieties arises from such processes. However, the empirical observation in §2.3 that large levels of $12\,\mu$m excess (which were quantified as $R_{12} > 3$) are only present in protoplanetary disks could indicate that debris-like processes can only supply a limited level of excess, and that gas must be present for higher levels (e.g., by aiding the radial transport of dust or by slowing down dust removal processes), which therefore provides some physical motivation (§2.4) for the observational classification proposed in §2.3 for the protoplanetary-debris transition.

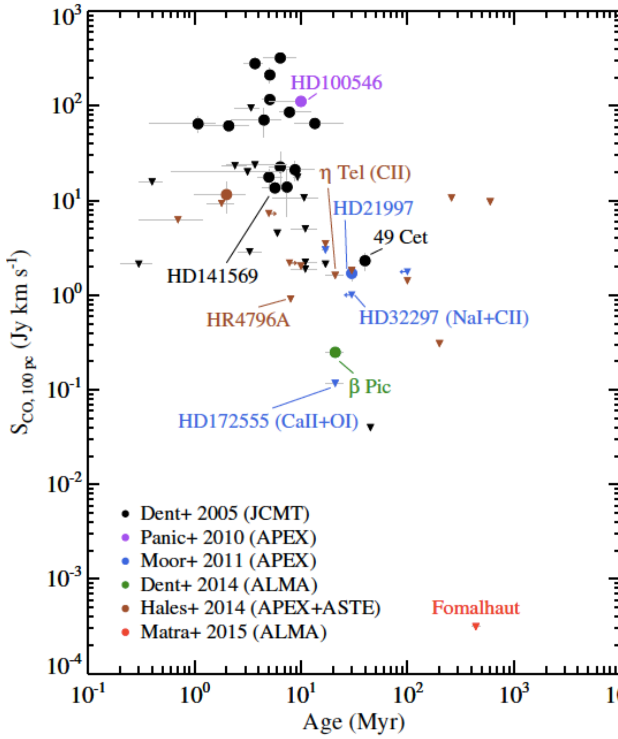

Fig. 4 Integrated intensity in the CO $J = 3$–2 line scaled to a distance of 100 pc as a function of stellar age for A and B-type stars with observations reported in the literature (i.e., including more stars than the samples in §2; adapted from Matrà et al. 2015). Filled circles are detections (coloured by their reference of origin as noted in the figure), and triangles are upper limits. Uncertainties are noted with grey lines, and are less than a factor of two in integrated intensities, while ages have similar uncertainties to those reported for Fig. 3.

3.4 Disappearance of gas

Measuring gas masses is extremely challenging in both protoplanetary and debris disks for different reasons. In protoplanetary disks, the bulk of the gas composition is inherited from the interstellar medium and hence its main constituent is H_2. However, even when H_2 is observed its emission only traces a minor fraction of the total disk mass (Thi et al. 2001; Carmona et al. 2011). While the second most abundant molecule (CO) is readily observed in HAe disks from the infrared to millimetre, CO millimetre lines are a poor indicator of disk gas mass because they are optically thick, though they are a useful diagnostic of the size and geometry of HAe disks (Panić and Hogerheijde 2009). The situation is improved for the optically thin low-abundance isotopes such as $C^{18}O$, however large uncertainties linked to the conversion to the total H_2 mass remain. This is particularly true in the outer disk region where the bulk of the mass resides and where low temperatures render CO invisible as it freezes out onto dust grains, but also in the surface layers of the disk, as these may be affected by selective photodissociation (Miotello et al. 2014).

In the case of debris disks, any gas that is detected may be secondary, i.e., released from large dust and planetesimals where it resides in the form of ice (e.g., Zuckerman and Song 2012). If so then the chemical composition of such gas would be markedly different from primordial gas, likely dominated by water and CO followed by the more complex species often observed in comets in the Solar system (e.g., Mumma and Charnley 2011). Similar to protoplanetary disks the most comprehensive searches for gas toward debris disks involve searches for CO millimetre lines, and in Fig. 4 we show the evolution of the integrated CO J =3–2 line intensity (scaled to 100 pc) as a function of stellar age including both classes of disk for all A and B-type stars for which observations are reported in the literature (Dent et al. 2005; Panić et al. 2010; Moór et al. 2011; Dent et al. 2014; Hales et al. 2014; Matrà et al. 2015). We already acknowledged that this observable does not have a one-to-one correspondence with the mass of CO in protoplanetary disks due to optical depth effects, and this is also true for debris disks but for different reasons. In debris disks the low gas densities result in poor coupling between the gas and the dust. This means that the gas excitation mechanisms and the processes that drive its dissipation are expected to be different from those in the higher density protoplanetary disk regime (Matrà et al. 2015). Nevertheless, even if the sample in Fig. 4 is significantly biased due to the limited number of stars that have been observed, it illustrates at what age and down to what level stars have been searched for this CO transition, which can be viewed as a useful (if flawed) proxy for gas mass, or at least as an indicator of significant gas levels.

Fig. 4 shows that it is generally the case that CO has not been detected around stars older than 10 Myr or those classed as debris disks. However, as acknowledged in §3.2, it is still present in some systems which have a depleted level of mass in mm-sized dust like HD141569 (Zuckerman et al. 1995; Dent et al. 2005). Moreover, there is a growing number of young debris disk systems for which CO has been detected. The most recent of these is β Pic for which CO had previously been detected along the line-of-sight to the star (Roberge et al. 2000; Troutman et al. 2011), but for which ALMA observations now reveal the CO distribution in emission (Dent et al. 2014). Crucially the spatial distribution of this gas was found to exactly match that of the dust. The radial distribution is extended over the same range of radii as the mm-sized dust (roughly 60-130 au), and the azimuthal distribution is highly clumped in a manner that matches that seen in mid-IR images of the distribution of small μm-sized dust (Telesco et al. 2005). Since both the μm-sized dust and CO gas are expected to be short-lived (the former due to radiation pressure and the latter limited to ~ 100 yr due to photodissociation from interstellar radiation), the natural conclusion is that both of these are products of collisions between planetesimals; i.e., the gas is secondary and continually replenished in the same way as dust in debris disks. While the exact mechanism for releasing the gas from icy planetesimals is unknown, analogy with comets in the Solar System, which can be $\sim 10\%$ CO by mass, shows that the inferred CO production rate of $0.1 M_\oplus$/Myr is reasonable as long as the majority of the CO ice is released as gas as mass passes down the collisional cascade.

In fact β Pic is the only one of the unbiased sample of 6 young A stars described in §2.2 to exhibit CO emission, with HR4796A having a limit of $7 M_\oplus$ when translated into molecular H_2 (Zuckerman et al. 1995; Greaves et al. 2000). However, two other young (30-40 Myr) debris disks, HD21997 and 49 Ceti, have CO detections at levels slightly above that of β Pic (see §2.2). For HD21997 ALMA observations show a distribution of CO that is not co-located with the mm-sized dust, rather the CO extends in significantly closer to the star (Kóspál et al. 2013; Moór et al. 2013). This suggests that the gas cannot be a product of planetesimal collisions, and instead must be primordial, which in turn raises the issue of why the CO has not been photodissociated on short timescales. In protoplanetary disks, the bulk of the disk material including CO is completely shielded from stellar irradiation and therefore the dissociation (and photoevaporation) is gradual, taking place only in the exposed surface layers of the disk. In the optically thin regime associated with debris disks, CO photodissociation would be expected to be more effective unless the CO molecules remain efficiently shielded by something other than dust. Whether the optically thin dust phase can be reached fast enough that the gas has not had time to completely disperse and so is present in sufficient quantities to effectively shield the CO remains an open question.

There are two other gas species detections amongst debris disks, and both lie in our young 6 A star sample (§2.2): HD172555 has a detection of OI, and η Tel has a detection of CII (Riviere-Marichalar et al. 2014). The origin of this gas, and in particular whether it is remnant primordial material or created in collisions, is unclear. For now we also do not know its radial location, and so whether its presence is perhaps related to the elevated levels of hot dust seen in both systems. However, it is a further indication that gas can persist to late times, and is one of the last things to disappear.

3.5 Formation of ring-like planetesimal structures

Images of the HR4796A debris disk show that the μm-sized dust in this 8 Myr system is concentrated in a narrow ring at $\sim$ 80 au (Wahhaj et al. 2014; Perrin et al. 2014), suggesting that the narrow ring-like structures (of fractional radial width $\Delta r/r \approx 10\%$) seen around older main sequence stars like 440 Myr Fomalhaut (Kalas et al. 2005) were put in place very early on. However, the observation of a narrowly confined ring of μm-sized dust does not necessarily imply that the same is true of the planetesimals from which the dust is produced. For example, that planetesimal disk could be much broader but contains just one location where dust is being produced, say the location where Pluto-sized planetesimals recently formed (Kenyon and Bromley 2002). Alternatively dust could be produced throughout a much broader planetesimal disk but the smallest dust is shepherded into a narrow region through interaction with a residual gas disk (Takeuchi and Artymowicz 2001; Lyra and Kuchner 2013).

Broad planetesimal disks (where $\Delta r/r > 1$) do not appear to be the norm amongst the population, as can be determined from the evolution of 24 and 70 μm excesses from main sequence A stars (Rieke et al. 2005; Su et al. 2006). These excesses get fainter exactly as expected if all A stars were born with narrow rings (Wyatt et al. 2007a), albeit at a different radius and with a different initial mass for different stars. This is because all such rings remain at roughly constant brightness until the largest planetesimals reach collisional equilibrium (which takes a time that depends on the radius and initial mass of the belt), whereupon the brightness falls off inversely with age. Broader planetesimal belts would exhibit a much different behaviour (Kennedy and Wyatt 2010), in particular exhibiting a much slower fall-off in far-IR brightness which is not observed. Since mm-sized dust is thought to trace the distribution of the planetesimals in a debris disk, the breadth of the planetesimal belt can be constrained in ALMA observations. [4] For now ALMA observations of the old narrow dust ring around Fomalhaut show its planetesimal population is also narrowly confined (Boley et al. 2012), but it has yet to be demonstrated that the same is true for younger systems for which different processes could be at play.

The general conclusion that debris disks are narrow does not exclude the existence of broad disks in some cases, and indeed one of the young A stars in §2.2 has a broad disk. Even though the disk of β Pic is seen edge-on, the ALMA continuum image can be deprojected using modelling to show that the mm-sized dust in this system is distributed over a factor of 3-4 in radius (i.e., $\Delta r/r \approx 1$), with a similar width inferred from the CO velocities (Dent et al. 2014). While it is tempting to interpret β Pic as having been caught in the act of evolving toward a narrow ring, the existence of older A stars with broad disks, such as γ Tri at 160 Myr (Booth et al. 2013) and κ CrB at 2.5 Gyr (Bonsor et al. 2013b), suggests that broad disks are simply another possible (though on average less common) outcome. However, it must be cautioned that some of the radial extent observed in debris disks, particularly at optical to far-IR wavelengths that are sensitive to μm-sized dust, may be attributable to radiation forces, and long wavelength observations are required to ascertain the radial width of the planetesimal belt.

It is worth noting that the existence of broad planetesimal belts does not preclude that the disks were born as much narrower rings, because the structure of a debris disk can be strongly influenced by interactions with planets in the system. For example, the planet-like object Fomalhaut-b was found to be on a highly elliptical orbit that takes it across the narrow debris ring (Kalas et al. 2013). Dynamical interactions would broaden the disk on a short timescale that depends on the planet's mass, but is of order Myr for planets larger than Neptune (Beust et al. 2014; Tamayo 2014). While this is a somewhat extreme configuration, simulations of interactions of debris disks with highly eccentric planets such as those which might originate from planet-planet scattering or merging events show that broad structures are a natural outcome (Pearce and Wyatt 2014). Moreover, the clump in the β Pic disk has been interpreted as evidence for outward migration of a planet on a circular orbit which swept planetesimals into its mean motion resonances (Wyatt 2003, 2006); that is, the disk's breadth could be a consequence of that migration. Thus it remains possible that all debris disks are born narrow and that those we see as

[4] This is because in a debris disk the same physics applies to all objects in the size range from planetesimals down to mm-sized dust, so as long as collisions do not change significantly the orbits of debris from those of their parent body, then the distribution of mm-sized dust should be the same as that of the planetesimals. This is not the case in a protoplanetary disk due to gas forces which result in the possibility that the distribution of mm-sized dust bears little resemblance to that of the planetesimals, as discussed in §3.2.

broad may just be those in which strong planet interactions have taken place. Alternatively planet interactions may aid concentration into a ring, particularly if there are planets at both the inner and outer edges, and ring breadth may serve as an indicator of shepherding planet mass (Rodigas et al. 2014).

High resolution imaging of azimuthal structure in young debris disks can be particularly telling of the processes involved in setting the distribution of planetesimals in debris disks and can have implications for the processes operating protoplanetary disks. For example if the clumpy structure in the β Pic disk is confirmed to originate in resonant trapping of planetesimals during a prior epoch of outward planet migration, then that migration potentially occurred during the protoplanetary disk phase; the secular evolution that lead to the warp of that disk must also have had its origins at an earlier epoch (see §2.4). In this respect it is notable that the clumpy structure in the β Pic disk bears similarities to those of transition disks, since in both cases the mm-size dust is seen to be concentrated in a clump, with smaller dust having an axisymmetric distribution (Telesco et al. 2005; Casassus et al. 2012; van der Marel et al. 2013; Dent et al. 2014). Given how close these systems are in evolutionary terms it might seem odd that the two structures have different physical origins, yet that is thought to be the case. The large mass of dust observed in the transition disk horseshoes likely precludes its origin in resonantly trapped planetesimals, and the low gas mass in β Pic likely precludes its clump having an origin in pressure-induced trapping.

The timing and mechanism for the planetesimals to become concentrated in a ring (or for planetesimals to become depleted at other locations) is not well constrained, as discussed in §2.4 and §3.2. For example, some planetesimals are likely to have been present in radially confined concentrations very early on in the protoplanetary disk phase, perhaps at the sites of snow-lines or pressure bumps (Ros and Johansen 2013; Drążkowska et al. 2013). Given the large amount of dust present in a protoplanetary disk, any planetesimal structures would be embedded in this and so only be revealed once the bulk of the dust had dispersed. However, it remains plausible that a significant population of planetesimals is created during dispersal of the protoplanetary disk (see §3.2).

4 Summary

This paper discussed the stages that occur as protoplanetary disks transition to debris disks. The picture that emerges has several caveats, notably with respect to the order of the stages and whether they take place consecutively or concurrently, but it is worth presenting a strawman evolutionary sequence to use as the basis for further discussion.

It is likely that both planetesimals and planet-sized objects are already present before the onset of the dispersal of the protoplanetary disk. This does not mean that they are necessarily present, just that if they form at all then this probably occurs before the transition. The existence of planetesimals is difficult to confirm, because they are masked by the large quantities of small dust that is also present, but we noted that these could be stirred by any planets present, and so that some of the small dust observed in this phase could arise from those planetesimals. The planets themselves may be easier to confirm, because their gravitational influence can leave discernable signatures on the disk structure (e.g., Wolf and D'Angelo 2005), but only if they are sufficiently massive.

The first stage is then the depletion of material from the inner regions of the disk. Accretion onto the star is ongoing in the transition disk phase, suggesting that these inner regions still contain gas, but are absent of small dust. Probably this occurs when the planetary system has grown sufficiently to curtail the replenishment of small dust in the inner regions, and to disrupt the inward flow of small grains from the outer disk through its effect on the gas disk structure (Pinilla et al. 2013; Owen 2014), though this explanation is not without problems (Clarke and Owen 2013).

The second stage is the depletion of the mm-sized dust from the outer disk. Whether this mass ends up in large objects (i.e., planetesimals or planets) or ground down into small dust is unknown, though this loss likely occurs quickly and from a mass budget perspective it is plausible that the majority of the mass ends up as planetesimals (see §3.2). The concentration of mm-sized dust in gas structures in transition disks could aid both scenarios (Birnstiel et al. 2013; Zhu et al. 2014).

Dust in the inner regions of systems beyond the transition disk phase is thought to be produced by the break-up of planetesimals and perhaps even planets, rather than a remnant of the protoplanetary dust. That is, moderate levels of hot dust can persist onto the main sequence, but this is a debris population. Hot dust with a debris-like origin can also be present in protoplanetary disks, and studying such dust at all evolutionary phases may provide a window into the possible presence and formation mechanism of small rocky planets close to the star, the statistics for which remain sparse for A stars (Lagrange et al. 2009; Johnson et al. 2011; Mulders et al. 2014).

One stage which is particularly unclear in its timing is the concentration of the planetesimals into a narrow ring, which is the most common outcome of the evolution (as opposed to a broad disk). This structure could have been imprinted early on in the protoplanetary disk phase, as appears to be the case in HL Tau, or fixed during the dispersal of the gas disk.

The last (and least understood) stage is the removal of the gas. The prevalence of gas around young A star debris disks shows that this component persists beyond the protoplanetary disk phase. However, most of this gas is thought to be secondary (i.e., released from its storage as ices in solid planetesimals) and so a debris-related phenomenon. Nevertheless, the persistence of gas around HD21997 which is probably primordial suggests that this is the last component to disperse.

We proposed that the distinction between protoplanetary and debris disks is primarily a question of the existence of large quantities of primordial gas, where we define large as being sufficient to entrain small dust grains in the disk and so damping collision velocities maintaining it at elevated levels. That is, the level of stirring in the disk is a consequence of the nature of the disk, but not its defining property.

Since the mass of the gas disk is difficult to measure the observational classification must rely on other tracers. We defined an empirical classification using flux ratios at 12 and 70 μm, with debris disks requiring $R_{12} < 3$ and $R_{70} < 2000$ (noting that this definition only applies to A stars). However, we also cautioned that interpretation of SEDs may be degenerate if the SED of a protoplanetary disk with an inner hole and a reasonable degree of dust settling is indistinguishable from that of a debris disk. Detailed study of the gas content in such systems would be needed to ascertain their evolutionary status.

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