Probing the final stages of protoplanetary disk evolution with ALMA

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ABSTRACT

Context. The evolution of a circumstellar disk from its gas-rich protoplanetary to gas-poor debris stage is not well understood. It is apparent that disk-clearing progresses from the inside-out on a short time-scale, and photoevaporation models are frequently invoked to explain this process. However, the photoevaporation rates predicted by recent models differ by up to two orders of magnitude, resulting in uncertain time-scales for the final stages of disk clearing.

Aims. The best candidates for studying this stage are weak line T Tauri stars (WTTS) with significant IR excess. We here aim to provide observational constraints on theories of disk-clearing by measuring the dust masses and CO content of a sample of such WTTS.

Methods. We use ALMA band-6 to obtain continuum and $^{12}$CO(2-1) line fluxes for a sample of 24 WTTS stars with a known IR-excess. For these systems, we infer the dust mass from the continuum observations, and derive disk luminosities and ages to allow comparison with previously detected systems.

Results. We detect continuum emission in only 4 of 24 systems, and no $^{12}$CO(2-1) emission in any. For those systems without a continuum detection, the dust mass and fractional disk luminosity upper-limits suggest they are in the debris disk regime, making them some of the youngest debris disks known. Of those with a continuum detection, three are possible photoevaporating disks but photodissociation has likely reduced the CO abundance to below our detection limit.

Conclusions. The low fraction of continuum detections implies that once accretion onto the star stops, the clearing of the majority of dust progresses very rapidly. Most WTTS with IR excess are not in transition but resemble debris disks. The dust in these disks is either primordial and survived the disk clearing, or is of second generation origin. In the latter case, the presence of giant planets within these systems might be the cause.

Key words. Protoplanetary disks – Planets and satellites: formation – Planet-disk interactions – Radio continuum: planetary systems – Radio lines: planetary systems – Infrared: planetary systems

1. Introduction

Circumstellar disks typically fall into two categories - the massive gas rich protoplanetary disks, and the gas-poor debris disks. Protoplanetary disks are a natural consequence of the star formation process, with the majority of their evolution being dominated by viscous accretion onto the star (e.g., Williams & Cieza 2011). They can be identified by their near and mid-IR excesses caused by their vast optically thick dust disks (e.g., Strom et al. 1989). Despite this, it is thought protoplanetary disks consist mainly of gas, with gas-to-dust mass ratios of ~100, similar to the ISM. The debris disks meanwhile, generally contain little or no detectable gas, with dust often confined to a narrow ring (see Wyatt 2008, for a review). It has long been suggested that debris disks could be a later stage of evolution from the protoplanetary disks, but the nature of the main physical processes which drive this evolution is ill-understood and remains one of the biggest questions in the field. To understand this phenomenon, the nature of a sub-class of disks, known as transition disks, needs to be investigated.

While a unique and universally accepted definition of what constitutes a transition disk (TD), does not exist, the most general definition is that of a T-Tauri disk with reduced excess emission at near to far infrared wavelengths relative to typical T-Tauri disks. Most TDs show significantly reduced fluxes at short wavelengths ($\lesssim 10 \mu m$) while still showing average emission at longer wavelengths. This observation is indicative of a dust cavity in the innermost region of the disk, and indeed submm images of TDs have proven this to be the case (Pietu et al. 2006, Hughes et al. 2007, Brown et al. 2009, Canovas et al. 2015). Such geometry requires a mechanism that can clear the dust from the "inside out", which is not consistent with the previously dominant mechanism of viscous accretion (Armitage et al. 1999). In addition, the life-
time of this transition stage must be short, i.e. ≲1 Myr as the detection rate of TDs is comparatively low, which again argues against the slow process of viscous accretion (Duvert et al. 2000; Wolk & Walter 1996; Andrews & Williams 2005; 2007). There have been many mechanisms suggested to explain the phenomena of TDs, including grain growth, giant planet formation and binarity. Although all these mechanisms likely contribute to disk evolution, in order to explain the final rapid removal of material at large radii, the most plausible mechanism is photoevaporation.

Initial theories of photoevaporation (e.g. Hollenbach et al. 1994; Clarke et al. 2001) described the photoionisation of hydrogen in the disks surface by extreme ultra-violet (EUV) photons. This photoionisation forms a pressure gradient which is able to drive mass loss in a photoevaporative wind beyond a critical radius, and evidence to support this theory has been found in observations of both [NeII] (Alexander 2008; Pascucci & Sterzik 2009; Ercolano & Owen 2010; Pascucci et al. 2011; Sacco et al. 2012) and [OI] lines (Font et al. 2004; Gorti et al. 2011; Rigliaco et al. 2013). Although this process is likely to be occurring throughout the disk lifetime, it only becomes significant when the accretion rate becomes comparable to the photoevaporation rate. When this happens, photoevaporation can open a gap, forming an inner and an outer disk. The inner disk, now cut-off from resupply, drains on a viscous timescale, thus creating the observed transition disk geometry (see Alexander et al. 2014, for a review). In the case of a transition disk however, the inner opacity hole allows radiation from the star to then reach the rim of the outer disk unimpeded, and complete the clearing of the disk on a short timescale of order 10^5 years (Alexander et al. 2006; Alexander & Armitage 2007).

Although a very promising theory, EUV photoevaporation suffers from an uncertainty in the EUV flux incident on the disk. The stellar EUV flux is difficult to measure as interstellar absorption prohibits direct observation of the ionizing photons. Furthermore, these ionising photons can be blocked by optically thick accretion columns or jets/winds, resulting in final estimates for the flux that can reach the disk varying by orders or magnitude (Herczeg 2007; Pascucci et al. 2012). Some recent advances in this area have used free-free emission from the disk to place limits on the EUV flux, and the results suggest EUV wavelengths are not sufficient to explain the [NeII] emission seen in some systems (Pascucci et al. 2014). Instead, the [NeII] emission is attributed to photoevaporation caused by a different wavelength of radiation. The other wavelengths included into photoevaporation models are X-rays (Owen et al. 2010; 2011; 2012) and far ultra-violet (FUV) (Gorti & Hollenbach 2008; 2009; Gorti et al. 2009), and a lot of debate surrounds which wavelength is most dominant. X-ray and FUV both predict the same evolutionary behaviour as EUV, but generally predict mass loss rates of magnitudes higher than the original EUV models, with $M_{\text{FUV}} \sim 10^{-10} M_\odot$ yr$^{-1}$ for EUV models, and $M_{\text{FUV}} \sim 10^{-8} M_\odot$ yr$^{-1}$ for FUV/X-ray (Gorti et al. 2009). Although stellar FUV and X-ray emissions are easier to measure than EUV, these models also suffer from uncertainties regarding disk chemistry and dust properties. FUV models for example, describe heating of the gas being dominated by PAHs, the abundance of depletion of which is difficult to determine (Geers et al. 2009).

In order to answer some of the questions surrounding photoevaporation models, a study of disks in their last stages of gas clearing is required. A natural sample in which to find such disks is in weak-lined T-Tauri stars (WTTS). Unlike the classical T-Tauri stars (CTTS), WTTS have a narrow Hα width, which is a strong indicator that the star is no longer accreting (or is accreting only at a relatively low level), and therefore lacks gas at radii close to the star (see also Pascucci et al. 2006; Ingleby et al. 2009). The majority of WTTS also have no IR excess, suggesting they have already cleared all their circumstellar gas and dust. A relatively small fraction however (~20%), do display an IR excess suggestive of a significant amount of dust (Cieza et al. 2007; Wahhaj et al. 2010), but a measurement of their dust mass has yet to be achieved. In a dedicated survey of transition disks selected from Spitzer (Cieza et al. 2010; 2012; Romero et al. 2012) only one such WTTS system was detected at (sub)mm wavelength (FW Tau), but observations of this particular system with ALMA recently revealed that the submm emission originates from an accreting third object. FW Tau should therefore not be considered a disk-possessing WTTS (Kraus et al. 2015). Furthermore, no previous studies have been able to measure the gas content of these disks, and whether WTTS with an IR excess (referred to as IR-WTTS) in the remainder of this paper are still photoevaporating their gas, or whether they are more akin to young debris disks has yet to be determined. Should they fall into the former class, these systems will indeed be in the final stages of their gas clearing, and observational constraints on their mass and gas-to-dust mass ratio will be invaluable to theories of photoevaporation. Should they fall into the latter class, these disks will be some of the youngest debris disks ever, and their ages can provide a constraint on the initial conditions of the debris disk phenomenon. Furthermore, if this result were to hold for a large sample of IR-WTTS, then this would suggest that by the time accretion ceases, the gas has either already been heavily depleted, or the remaining gas is photoevaporated rapidly. In this sense, such a result would have great significance to both photoevaporation theory and disk evolution in general.

Here, we present one of the first detailed studies of WTTS with IR excess with ALMA. We use Band 6, observing both the continuum and the 12CO(2-1) transition, with the aim of identifying the evolutionary state of these WTTS disks and imposing limits on photoevaporation theory.

## 2. Observational procedure

### 2.1. Target selection

Our sample consists of 24 pre-main-sequence stars (based on weak Hα emission and Li I absorption) in nearby (≈200 pc) molecular clouds (see Table 1). The objects have been classed as WTTS based on the velocity widths of their Hα lines. The Hα line provides a reliable, distant independent indication of a stars accretion, with accretion producing broad, asymmetrical Hα emission. Non-accreting objects will still produce Hα emission of chromospheric origin, but it tends to be comparatively narrow and symmetric. The empirical dividing line between accreting and non-accreting has been a matter of some debate, with some claiming accreting systems have a 10% peak width of >270 kms$^{-1}$, and others claiming a dividing line of >200 kms$^{-1}$ which varies with spectral type (Martín 1998). The systems in this study were selected as they all either have 10% peak widths less than 200 kms$^{-1}$, or instead display Hα absorption lines, allowing them to be identified as very likely non-accretors. They all lack considerable IR excess at ~10 μm or shorter wavelengths, but show weak yet robust (>5-10 σ) excesses in the mid and/or far-IR from Spitzer, WISE, and/or Herschel. These targets have been labelled as either photoevaporating transition disks, or debris disks candidates based on their fractional disk luminosities (Wahhaj et al. 2010; Romero et al. 2012; Cieza et al. 2010; 2012). Binaries with wide projected separations were in-
Table 1. Sample parameters

| No. | 2MASS ID     | Cloud      | Distance (parsec) | Spectral Type | Hα width (km s\(^{-1}\)) | Ref. | Binary sep. (arsecs) | Binary ref. |
|-----|--------------|------------|------------------|---------------|-------------------------|------|---------------------|-------------|
| 1   | 04182147+1658470 | Taurus     | 135±20           | K5            | Absorp.                 | 1    | ...                 | ...         |
| 2   | 04192625+2826142 | Taurus     | 135±20           | K7            | 180                     | 2    | ...                 | ...         |
| 3   | 04242321+2650084 | Taurus     | 135±20           | M2            | 200                     | 3    | ...                 | ...         |
| 4   | 04314503+2859081 | Taurus     | 135±20           | F5            | Absorp.                 | 3    | ...                 | ...         |
| 5   | 04325323+1735337 | Taurus     | 135±20           | M2            | 138                     | 2    | ...                 | ...         |
| 6   | 04330422+2921499 | Taurus     | 135±20           | B9            | Absorp.                 | 3    | ...                 | ...         |
| 7   | 04364912+2412588 | Taurus     | 135±20           | F2            | Absorp.                 | 3    | ...                 | ...         |
| 8   | 04403979+2519061 | Taurus     | 135±20           | M5            | 130                     | 3    | ...                 | ...         |
| 9   | 04420548+2522562 | Taurus     | 135±20           | K7            | 94                      | 4    | 0.3                 | 7           |
| 10  | 08413703-7930304 | η Chamaleon | 97±3             | M3            | Absorp.                 | 5    | ...                 | ...         |
| 11  | 08422372-7904303 | η Chamaleon | 97±3             | M3            | Absorp.                 | 5    | ...                 | ...         |
| 12  | 11073519-7734493 | Chamaleon I | 160±15           | G8            | Absorp.                 | 1    | 0.247               | 8           |
| 13  | 11124268-7722230 | Chamaleon I | 160±15           | M5.25         | 162                     | 6    | 2.8                 | 9           |
| 14  | 16002612-4153553 | Lupus IV   | 150±20           | G8            | Absorp.                 | 4    | ...                 | ...         |
| 15  | 16010896-3320141 | Lupus I    | 150±20           | K7            | 132                     | 4    | ...                 | ...         |
| 16  | 16031181-3239202 | Lupus I    | 150±20           | M6            | 189                     | 6    | 2.8                 | 9           |
| 17  | 16085553-3902339 | Lupus III  | 200±20           | K8            | 131                     | 4    | 1.0                 | 10          |
| 18  | 16124119-1924182 | Ophiuchus  | 119±6            | M3.7          | 132                     | 6    | 1.83                | 6           |
| 19  | 16220961-1953005 | Ophiuchus  | 119±6            | M2.5          | 128                     | 4    | ...                 | ...         |
| 20  | 16232757-2345508 | Ophiuchus  | 119±6            | M0            | 206                     | 4    | ...                 | ...         |
| 21  | 16251469-2456069 | Ophiuchus  | 119±6            | K7            | 151                     | 2    | 0.480               | 11          |
| 22  | 19002906-3656036 | Corona Australis | 129±11        | M4            | 93                      | 6    | 0.132               | 12          |
| 23  | 19012901-3701484 | Corona Australis | 129±11        | M3.75         | 83                      | 6    | 0.5                 | 6           |

Notes. The targets were identified from the following papers, in which their photometry and Hα widths can be found: 1 - Nguyen et al. (2012), 2 - Cieza et al. (2013), 3 - Cieza et al. (2012), 4 - Wahhaj et al. (2010), 5 - Sicilia-Aguilar et al. (2009), 6 - Romero et al. (2012). The binary systems were identified in the following papers: 7 - Leinert et al. (1993), 8 - Lafrenière et al. (2008), 9 - Merín et al. (2008), 10 - Prato (2007), 11 - Ratzka et al. (2005), 12 - Köhler et al. (2008).

2.2. ALMA observations

Observations of the above systems were performed in Band 6, with systems 14, 17, 19, 23 and 24 being observed in Cycle 0 (2012), and the remaining in Cycle 1 (2013). Cycle 1 observations were split into 3 based on their host cloud, with the Lupus/Ophiuchus systems in one group, Taurus in another, and Chamaleonis in the final group. These groups were observed at different times and with slightly different parameters. Table 2 gives a summary of these observational set-ups.

We chose to observe the 12CO(2-1) line, as it is highly sensitive to the presence of circumstellar gas out to large radii, where the bulk of the gas should be located. We obtained one epoch observation for all systems, with the correlator configured to obtain one baseband centered on 230.52 GHz which was aimed at detecting the 12CO(2-1) spectral line, and three continuum basebands centered at 228.52, 214.52, and 212.52 GHz. However, a fault with the local oscillator during the Cycle 0 observations meant that only the 230.52 and 228.52 GHz basebands could be observed. The total bandwidth for the observations was 3.75 GHz for the Cycle 0 and 7.5 GHz for Cycle 1 observations, with a unique spectral resolution of 976.56 kHz in 3840 channels for each 1.875 GHz baseband. In all cases, the requested rms was set at 0.16 mJy for the continuum, and 30 mJy for each individual velocity channel (and thus for the 12CO(2-1) line). Standard calibration steps were applied to the data, and we obtain the final images by deconvolving the set of visibilities with the CLEAN task implemented in CASA (McMullin et al. 2007), using natural weighting.

3. Results

3.1. Disk dust masses

Only 4 of our 24 systems have detectable continuum above the 3σ level, with the addition of one tenuous detection in system 8. This system displays weak emission located on the source, but...
Table 2. Observation log

| Date       | Cloud     | Antennas | Time on Antennas (min) | Antennas flagged | Bandpass Gain | Phase Gain | PWV | Min/Max baseline (m) |
|------------|-----------|----------|------------------------|------------------|--------------|------------|-----|---------------------|
| 12/06/17   | Lup/Op/CrA | 20       | 4.54                   | ...              | J1733-1304   | Neptune    | 1.41| 21.2/402.3          |
| 13/11/01   | Lup/Op    | 29       | 2.07                   | DV19,08,06       | J1924-2914   | Neptune    | 1.60| 17.3/991.5          |
| 13/12/04   | Taurus    | 27       | 3.60                   | DV08             | B0420-0127   | J0510+180  | 5.11| 15.8/462.9          |
| 13/12/18   | Cha       | 23       | 4.16                   | DV19,08          | B1104-445    | Ceres      | 2.31| 15.14/991.5         |

Andrews & Williams (2005) show that, owing to continuum emission being optically thin at mm wavelengths, the dust mass can be estimated by a simple equation of the form $M_{\text{dust}} = C_\nu \times F_\nu$, where $C_\nu$ is a constant for a given frequency $F_\nu$. We adopt the constant derived for 1.3mm by Cieza et al. (2008), and use the equation

$$M_{\text{dust}} = 0.566 \times \left[ \frac{F_\nu(1300)}{m\text{Jy}} \left( \frac{d}{140\text{pc}} \right)^2 \right] M_\odot \quad (1)$$

which is just below the 3 sigma level and therefore not significant enough to claim a detection. Andrews & Williams (2005) show that, owing to continuum emission being optically thin at mm wavelengths, the dust mass can be estimated by a simple equation of the form $M_{\text{dust}} = C_\nu \times F_\nu$, where $C_\nu$ is a constant for a given frequency $F_\nu$. We adopt the constant derived for 1.3mm by Cieza et al. (2008), and use the equation

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allows for meaningful comparisons with previous results. The results of this are displayed in Table 3. In the case of a non-detection, we quote the 3 sigma value as our upper limit, with this uncertainty being dominated by the uncertainty in distance to the system.

3.2. $^{12}$CO(2-1) non-detections

We did not detect $^{12}$CO(2-1) emission for any of the observed systems and so if there is any CO, then it remains below the detection limit of ALMA. Determining the mass of CO that this non-detection implies is considerably more difficult than for the dust however, as $^{12}$CO(2-1) emission is often optically thick. Converting this CO upper limit into a gas upper limit is an even greater challenge, as the relative abundance of CO to H$_2$ (the
component which makes up the majority of the gas mass) is uncertain. Although the ISM value is usually assumed, these disks have low enough column densities that photodissociation could act to deplete the CO abundance. To investigate this possibility further, we compare our systems to the grid of disk models of Williams & Best (2014), which predict photodissociation fractions and CO fluxes for a range of disk parameters. We assume an ISM gas-to-dust ratio of 100 to calculate the gas masses for our disks, using the 3-sigma upper limit on dust mass in the case of non-detections. We then explore the regions of this grid with the calculated gas mass, a 0.5 M⊙ of non-detections. We then explore the regions of this grid with our disks, using the 3-sigma upper limit on dust mass in the case further, we compare our systems to the grid of disk models of certain. Although the ISM value is usually assumed, these disks emission is due to contamination of this star (suitable for the stellar power law in frequency, $\nu$ , which measures the fraction of the stars radiation that is intercepted and re-emitted by the disk. Typical values for protoplanetary and debris disks is much lower, with typical values for debris disks is much lower, with typical values for protoplanetary disks are in the region $D/L_\star \sim 10^{-6}$ to either one or two blackbodies, as required. At wavelengths longer than $\sim 70 \mu m$, the emission from an optically thin debris disk is observed to deviate from a simple blackbody by a power law in frequency, $\nu^\beta$ (Hildebrand 1983). A typical value of $\beta$, also known as the spectral index, is 2 for ISM like material. An equation of the form

$$S_\nu = \Omega N (\frac{\nu}{\nu_0})^\beta B_\nu(T)$$

(2)

### 3.3. Stellar Ages

For comparison to previously studied systems, and to impose limits on disk clearing time-scales, the stellar ages are required. This was achieved by calculating stellar luminosities and temperatures, and then comparing to the PMS isochrones of Siess et al. (2000). Stellar temperatures were estimated by their spectral type, using the scale provided by Kenyon & Hartmann (1995). The stellar luminosity was calculated by first applying a bolometric correction to each star appropriate for its spectral type, again in accordance with the values provided by Kenyon & Hartmann (1995). The J band magnitude was used as a reference as this band is less effected by extinction than at shorter wavelengths, whilst having little chance of being affected by the flux from any circumstellar material. These corrected flux values were then used to calculate the luminosities, assuming the distances in Table 1. The results of this process are displayed in Table 4. Four systems (1, 4, 6 and 7) appeared too under-luminous for their temperature to coincide with any PMS model, and were therefore omitted.

Some caution has to be taken when interpreting these ages, as the evolutionary tracks for these PMS systems lie close together on the Hertzsprung-Russel diagram. Moreover, the distances to the individual objects have an uncertainty of up to ~15%, which can introduce a ~30% uncertainty into the intrinsic luminosity of the object. These effects can conspire to result in a large uncertainty in the ages of individual stars. Fortunately however, the ages of WTTS are considerably easier to determine than for CTTS. CTTS are effected by veiling and possess highly heterogeneous photospheres due to their accretion, which makes their intrinsic luminosities and temperature much more challenging to determine (Cieza et al. 2005). In the case of our WTTS the largest contributor to the uncertainty is likely the distance to the object.

### 3.4. Fractional Disk Luminosities

A frequently used criterion for distinguishing between protoplanetary and debris disks is the fractional disk luminosity, $L_{D}/L_\star$, which measures the fraction of the stars radiation that is intercepted and re-emitted by the disk. Typical values for protoplanetary disks are in the region $L_{D}/L_\star \sim 0.1$, whereas the value for debris disks is much lower, with typical values $L_{D}/L_\star \lesssim 10^{-5}$. To determine this quantity for our sample, we fit the disk emission ($L_{D}$) to either one or two blackbodies, as required. At wavelengths longer than $\sim 70 \mu m$, the emission from an optically thin debris disk is observed to deviate from a simple blackbody by a power law in frequency, $\nu^\beta$ (Hildebrand 1983). A typical value of $\beta$, also known as the spectral index, is 2 for ISM like material.

An equation of the form

$$S_\nu = \Omega N (\frac{\nu}{\nu_0})^\beta B_\nu(T)$$

(2)
Fig. 2. Images generated by the CLEAN algorithm for the four systems in which we detected continuum emission. The black cross denoted the position of the target, with the white cross as the approximate position of any potential binary companions. The white ellipse denote the beam size. The panel above each image displays spectra centred on the $^{12}$CO(2-1) line for these regions, which can be seen to contain only noise.

was therefore used, where $\Omega$ is the solid angle of the emitting region, $N$ is the column density of dust, $\nu$ the frequency and $B_\nu(T)$ is the emission of a blackbody at a temperature $T$. With values of $N$, $T$ and spectral index $\beta$ all being allowed to vary, the results become degenerate and therefore cannot be used to infer any specific disk properties. The total disk flux density however, is well approximated by this simple prescription. The stellar flux density was likewise fit assuming a blackbody spectrum of the stars temperature and normalised to the J band flux. Both flux densities were then integrated according to Simpsons rule and divided to obtain the fractional disk luminosity.

In the case of disk excess only being detected at one wavelength, the value of $L_D/L_*$ is extremely unconstrained. However, an upper limit was calculated by assuming a value of $\beta=2$, and fitting the blackbody with regards to the upper limits from ALMA and/or Herschel.

3.5. SEDs and Individual System Parameters

Systems with Detections (2, 14, 17, 23)

The SED for the 4 systems in which 1.3mm emission was detected are shown in Fig. 1. System 2 has a fractional disk luminosity which is very low, and is therefore likely a massive debris disk. For the other 3 systems however, the mid to far-IR slope is suggestive of extended dust disks and not the thin-belts often seen in debris disks. These 3 systems are therefore the most likely to be undergoing photoevaporation, and further observations with a deeper detection threshold for the detection of gas will be invaluable.
An interesting feature of these 3 systems is that they are all believed to be in wide binaries, although there is only single-epoch data available for these systems so their binary nature has not been confirmed via proper-motion (Merín et al. 2008; Köhler et al. 2008). Assuming that they are indeed binaries, one has to be careful in interpreting where the excess emission originates from. For system 17, the projected separation is large enough that the photometry short of 10 \(\mu m\) is resolved (the Spitzer resolution at 8 \(\mu m\) is \(\sim 2''\)), as well as the mm photometry reported in this paper. The 24 and 70 \(\mu m\) points should be treated with some caution, but as no 1.3 mm emission was detected for this alleged binary companion (see Fig. 2), it is likely that emission at all wavelengths traces a single circumstellar disk. A similar argument applies to system 14, although the ALMA image does hint at some emission from the approximate location of the binary companion, which may contributing to the 24 \(\mu m\) flux found for this target as well. Given the wide separations of these targets, with projected separations of \(\sim 420\) and 560 au, it is unlikely that the tentative binary companion would influence the circumstellar disk evolution considerably, as Harris et al. (2012) found no difference in disk luminosity for disks in wide binaries (separations \(\geq 300\) au) compared to those around single systems.

For system 23, the projected separation is small enough that all detected excess emission is unresolved, and could originate from either circumstellar disks, or a single circumbinary disk. In either case, if the true separation of this system is \(\lesssim 40\) au, it is likely that any disks will undergo a very different evolution compared to disks around single stars. Observations suggest binaries of separations \(\lesssim 40\) au inhibit the formation of protoplanetary disks (Kraus et al. 2012), but disk-possessing close binaries can be found, and there is evidence to suggest the tidal torque from such a binary could even slow down disk evolution and cause prolonged lifetimes for the disk material (Alexander 2012), which may help explain this particular detection. For all systems however, the binary nature of these objects needs to be confirmed and the sample size increased before conclusions can be drawn about how binarity effects this final stage of a disks lifetime.

Systems 14 and 17 are the only systems in our sample which contain excess emission at 12 \(\mu m\), suggesting the presence of dust located at small radii. Indeed, the other mid-IR detections of these 2 systems only deviate slightly from the average disk emission in Taurus and this, coupled with the fact that these 2 systems have the highest detected dust mass, makes them the most likely to have recently ceased accreting and be in the final stages of gas clearing. As mentioned in section 3.2, the lack of a CO detection in these systems does not exclude its existence, as photodissociation has likely reduced the abundance so that emission is below our detection limit.
Systems with large mid-IR excess (7, 9, 13, 21)

Systems 7, 9, 13 and 21 all have published 70 µm detection, and steep rises in the MIR, which is suggestive of a large population of cold dust (see Fig. [5]). Due to this, the ALMA nondetections are rather surprising. We therefore include the blackbody fits used to determine their fractional disk luminosity into Fig. [3] to investigate if the value for the spectral index must be \( \beta \gg 2 \). All fall below or on the ALMA upper limit with a spectral index \( \beta \leq 2 \), with the exception of system 13, for which a value of \( \beta \geq 3.2 \) was required to satisfy the upper limits. This rather large value of beta suggests that the far-IR points of this system are not associated with the source, and Matrà et al. (2012) show that wavelengths long of 70 µm could be dominated by a source south-west of the system. Accounting for this, we find only a single blackbody of \( T = 85K \) and \( \beta = 2 \) is required to fit the emission of this system.

For system 7, an F2 type star, our age analysis found no PMS tracks consistent with its luminosity, suggesting it is perhaps not a member of the young cloud and is already on its main-sequence. Massarotti et al. (2005) support this hypothesis by showing that the proper motion of this system is indeed too high to be part of Taurus. The high proper motion makes it likely that this system is in fact a foreground main sequence star of a later spectral type and with less extinction.

System 9 and 21 both have excess which begin at 70 µm, suggesting a population of dust far from the star. System 9 can easily be explained by material in a thin belt, and is therefore likely a cold debris disk, albeit a very young one. The 160 µm point obtained for system 21 requires an even cooler debris disk of \( \sim 20K \) to explain all flux, corresponding to a distance of \( \sim 600 \) au. This is extremely far from the star, so is unlikely to be occurring. Instead, it is more likely that the 160 µm point includes contamination from extend emission in the Herschel image from which it was derived (Cieza et al. 2012). In any case, both systems can be fit with a spectral index \( \beta = 2 \), consistent with dust similar to the ISM.

If the emission in 13 and 21 are indeed due to another source, then its likely all of these 4 systems are in their debris phase. This is also apparent from their fractional disk luminosities, which are of order \( 10^{-3} \). A deeper search with ALMA would clarify the situation for these uncertain objects, as it could both detect and resolve the continuum emission to a much smaller area than possible with Herschel. System 7 is perhaps the least certain however, with a relatively high fractional disk luminosity and some uncertainty on its spectral type. If it transpires that it is a late-type star, then the fractional disk luminosity will be increased and this object would need to be reclassified.

Likely debris disks

For the remaining systems (Fig. [4]), only one or 2 excess points exist, and the upper limit on the 1.3mm flux is not so restrictive, so it is easy to explain the excess as originating from a single temperature blackbody. The value of \( L_D/L_\ast \) is confined to the debris regime, but it is difficult to class these objects as debris.
disks without knowledge of their gas content. Although our CO non-detections cannot say for sure if there is still a large amount of H$_2$ gas present, previous studies have searched directly for H$_2$ tracers in similarly young, low mass systems and found nothing within a few au of the star (Ingleby et al. 2009). For example, Pascucci et al. (2006) were able to rule out gas masses above 0.04 $M_\odot$ within 3 AU of the inner disk radius for the disks in their sample, which include disks in a similar 5-15 Myr range. They conclude that gas dissipation is very efficient, so it would be surprising if the gas has survived in the low mass systems in our sample. We therefore consider it most likely that the majority of these systems are in their debris stage, containing only thin belts of dust and no gas. Systems 1, 4 and 6, which all appeared too under-luminous to fit a PMS track, are likely also very well mixed in age resulting in only a weak trend in their parental cloud. This interpretation is still rather uncertain however, as both on-cloud and off-cloud sources in the survey are very well mixed in age resulting in only a weak trend in age as a function of separation. Instead, the majority of both ob-

Fig. 5. Comparison of the dust mass in our systems compared to those in the literature. Green symbols denote those with detected flux and red those with upper-limits. Black symbols which lie above the dotted line correspond to known protoplanetary disks (data taken from Wyatt et al., Ricci et al. 2010, Romero et al. 2012). Black symbols in the lower portion correspond to known debris disks (data taken from Greaves et al., Liu et al. 2004, Lestrade et al. 2006, Williams & Andrews 2006, Matthews et al. 2007). Black symbols which lie above the dotted line correspond to known debris disks (data taken from Greaves et al., Liu et al. 2004, Lestrade et al. 2006, Williams & Andrews 2006, Matthews et al. 2007).

4. Discussion

4.1. WTTS as young Debris Disks

Figure 5 compares the age of the systems in our sample to the dust mass derived from the mm observations, and our upper limits clearly show that the dust masses of most of our objects will lie in the debris disk regime. Furthermore, the fractional dust luminosity of all systems except 3 seem to lie in the debris regime (see Table 3), with values of $L_D/L_*$ $\leq 3 \times 10^{-3}$. Even system 2, in which there is a detection at 1.3 mm, has a value which places it in the debris regime, making it likely a high-mass debris disk rather than a photoevaporating disk. Taking the broad definition of a debris disk, in which they are defined as gas-poor, geometrically thin dust disks at uniform temperature, then the previously youngest known debris disks have ages in the range of 7-10 Myr. The systems observed here however, have younger ages with 12 systems in the age range 1.8$_{-0.3}^{+1.5}$ to 6.7$_{-2.7}^{+2.3}$ Myr. Even accounting for the intrinsic uncertainty in these ages, they are significantly lower than previous debris disks, and this raises questions as to why such youthful disks have not previously been observed. This is quite possibly the result of observational bias, as debris disk emission is intrinsically faint and as such, observations are limited to nearby stars. The arrival of ALMA however, now allows us to open this parameter space to the young clusters at much farther distance of $\gtrsim 100$ pc and our results clearly hint that rapid evolution into the debris phase is possible even for late spectral types. If confirmed, then these systems will lower the minimum age of debris disks, and indicate a larger range of time-scales for protoplanetary disk evolution.

A more restrictive definition of debris disks describes them as containing second generation dust, formed through a continuous process of collisions between planetesimals, and subsequent removal through radiation pressure and Poynting-Robertson drag (Wyatt 2008). Under this definition, it is unclear if the disks in our sample would be classed as debris. Wahhaj et al. (2010) suggest that dust around WTTS is primordial based on the lower fraction of IR-WTTS found for off-cloud sources compared to on-cloud. They suggest that this is caused by dissipating primordial dust, as there is a link between separation from the cloud and age, with the older WTTS located at increased separation from their parental cloud. This interpretation is still rather uncertain however, as both on-cloud and off-cloud sources in the survey are very well mixed in age resulting in only a weak trend in age as a function of separation. Instead, the majority of both ob-
servational evidence and photoevaporation models suggest that dust in the inner and outer regions of disks dissipates nearly simultaneously (e.g. Andrews & Williams 2005; Alexander & Armitage 2007), and most models of photoevaporation do not allow a considerable amount of dust to be left behind. This therefore suggests that the debris disks seen around WTTS contain second generation dust. It has been suggested that that a large portion of the dust in protoplanetary disks could even be second generation, based on the observation that the growth of grains from micrometer to meter sizes should occur very rapidly (Dominik et al. 2007). This would quickly reduce the dust mass of protoplanetary disks inferred from IR observations, and yet this value remains fairly constant for a range of disk ages (Natta et al. 2007). A mechanism of dust replenishment is therefore required in protoplanetary disks (Dullemond & Dominik 2005), and we consider it likely that the debris disks in our sample contain second generation dust as well.

The observed fraction of the WTTS population which display an excess (∼20%) is similar to the fraction of debris disks found around young FGK type stars of between 10-16% (Hendenbrand et al. 2008; Trilling et al. 2008). Although it is often assumed that IR-FTTS evolve into those without, an alternative possibility is that these IR-WTTS mostly contain a debris disk of second generation origin, and this debris disk can then persist into its main sequence lifetime. The WTTS without excess would then make up an entirely different population, and the difference between these 2 populations could be that the former has a method of stirring the disk, which is a requirement for the collisional cascade that form debris disks. Stirring via stellar flybys (Kenyon & Bromley 2002) and self-stirring via 1000 km sized planetesimals (Kenyon & Bromley 2002) are both possible causes for this. Perhaps the most exciting explanation for WTTS with debris disks however, is that these systems have formed giant planets capable of stirring the disk (Mustill & Wyatt 2009). This would require giant planets orbiting at a few au, and the occurrence for such bodies around FGK stars has been estimated from radial velocity surveys at between 12-22% (Llinarex & Grether 2003; Marcy et al. 2005; Cumming et al. 2008). This similarity of this occurrence rate with the fraction of WTTS systems that possess debris disks makes such systems an excellent places in which to perform planet searches.

4.2. Implications for Photoevaporation Models

Some models of X-ray photoevaporation predict a sample of "reluc" transition disks with large cavities and high dust masses which persist for ≥10 Myr (Owen et al. 2011). Our findings add to the growing body of research against this prediction (e.g. Mathews et al. 2012; Cieza et al. 2010, 2012), as the vast majority of our IR-WTTS have no detectable 1.3 mm emission despite their ages being under 10 Myr. Some of the more recent X-ray photoevaporation theories introduce a mechanism they call "thermal sweeping", which disperses the remaining material in these massive dust disks in a small fraction (1-3%) of the disks total lifetime (Owen et al. 2013), and removes the prediction of these relic disks. Likewise, the EUV models of photoevaporation predict short time-scales for final disk clearing. EUV models predict much lower photoevaporation rates in general, but are also only capable of forming transition disks when viscous accretion has already cleared a large amount of material. The resulting disks predicted by EUV models are therefore of lower mass than in the X-ray case, and clearing can progress on time-scales of between 1-10% of the disk lifetime (Alexander & Armitage 2007).

Previous surveys of WTTS have found that ∼20% of WTTS display an excess, which when compared to the number of CTTS in the same regions, suggests the disks around WTTS persist for 10-20% of the disk lifetime before moving into a diskless state (Cieza et al. 2007; Wahhaj et al. 2010). This percentage is somewhat higher than that predicted by photoevaporation models, but its derivation assumes that all IR-WTTS follow the same evolution, moving from a CTTS, to an IR-WTTS and finally to a diskless state. If, as outlined above, the WTTSs with debris disks are not in transition, then the apparent rarity of photoevaporating disks will significantly lower this percentage and may bring it more in-line with photoevaporation models. The small number of detections and lack of gas-confirmation in our potential photoevaporating disks does not allow accurate estimation of this corrected percentage, but a wider survey of these photoevaporating disks may confirm this tentative result.

4.3. Comparison to known Debris Disks with Gas

In recent years, a small population of debris disks have been found with detectable gas, leading to some debate as to its origin. As with the dust, the origin of this gas is believed either primordial, or formed through collisions of icy comet-like objects. 49 Ceti is one such system, with spectral type A1, a dust mass of ∼0.3 M⊙ and a 12CO(2-1) integrated intensity of 2.0 Jy km s⁻¹ (Hughes et al. 2008). Its age has proved difficult to determine, as it is not obviously a member of any associations, but [3] et al. (2001) believe it is a PMS with an age of 8 Myr, opening up the possibility that it is a high-mass analogy to the stars in our sample. If 49 Ceti were at the distance of Taurus however, we would expect to detect this level of CO. Likewise, the 30 Myr old, A4 type system HD21997 is classed as a debris disk, containing only 0.09 M⊙ of dust, and yet it displays CO emission which we would have conclusively detected in our survey (Kospal et al. 2013). If these systems truly are harbouring primordial gas, then the evolution for A-type stars must be drastically different to late-type stars to allow them to retain such a large quantity of gas at such low dust masses. Alternatively, the dust is secondary, and both A type stars and most of the late type stars in this survey lose their gas by ages of ≤10Myr.

5. Conclusion

All the above sources in our sample are beyond the stage of active gas accretion. TheirSED’s are suggestive of a depleted dust mass, and we here confirm this either with the low 1.3 mm flux, or with the ALMA non-detection. The dust for all systems must have therefore either been largely removed or agglomerated into larger particles. The non-detection of CO lines in all systems is suggestive of a similar fate for the gas, having likely been removed by photoevaporation. However, some caution should be taken with this assumption, as photodissociation models of such low predicted gas masses suggest the CO abundance will be lowered. We find that for system 17 (that with the highest dust mass), these models of photodissociation still predict an appreciable level of CO, but our observations were simply not sensitive enough to detect it. This system, and others like it, therefore warrant particular attention in further surveys, as they offer the best possibility of us observing the final gas-clearing of the disk.

For the systems in which there was no 1.3mm detection, it is likely that they are free from gas and contain dust masses and distributions similar to debris disks. This is apparent from a comparison of their fractional disk luminosities and dust mass upper-limits to that of known debris disks, as both clearly lie in
the debris disk regime. These systems however, are clearly much younger than the majority of debris disks allowing for more strict constraints on debris disk formation time-scale than ever before. A deeper study with ALMA will be invaluable to conclusively determine their evolutionary state, as well as confirm the dust masses of the suspected debris disks.

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References

Alexander, R. 2012, ApJ, 757, L29
Alexander, R., Pascucci, I., Andrews, S., Armitage, P., & Cieza, L. 2014, Protostars and Planets VI, 475
Alexander, R. D. 2008, MNRAS, 391, L64
Alexander, R. D. & Williams, J. P. 2007, ApJ, 671, 1800
Alexander, R. D., Clarke, C. J., & Pringle, J. E. 2006, MNRAS, 369, 229
Andrews, S. M. & Williams, J. P. 2005, ApJ, 631, 1134
Andrews, S. M. & Williams, J. P. 2007, ApJ, 671, 1800
Armitage, P. J., Clarke, C. J., & Tout, C. A. 1999, MNRAS, 304, 425
Brown, J. M., Blake, G. A., Qi, C., et al. 2009, ApJ, 704, 496
Canovas, H., Schreiber, M. R., Cáceres, C., et al. 2015, ArXiv e-prints
Cieza, L., Padgett, D. L., Stapelfeldt, K. R., et al. 2007, ApJ, 667, 308
Cieza, L. A., Kessler-Silacci, J. E., Ja

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