Do two-temperature debris discs have multiple belts?

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ABSTRACT

We present a study of debris discs whose spectra are well modelled by dust emission at two different temperatures. These discs are typically assumed to be a sign of multiple belts, which in only a few cases have been confirmed via high-resolution observations. We first compile a sample of two-temperature discs to derive their properties, summarized by the ratios of the warm and cool component temperatures and fractional luminosities. The ratio of warm to cool temperatures is constant in the range 2–4, and the temperature of both warm and cool components increases with stellar mass. We then explore whether this emission can arise from dust in a single narrow belt, with the range of temperatures arising from the size variation of grain temperatures. This model can produce two-temperature spectra for Sun-like stars, but is not supported where it can be tested by observed disc sizes and far-infrared/mm spectral slopes. Therefore, while some two-temperature discs arise from single belts, it is probable that most have multiple spatial components. These discs are plausibly similar to the outer Solar system’s configuration of Asteroid and Edgeworth–Kuiper belts separated by giant planets. Alternatively, the inner component could arise from inward scattering of material from the outer belt, again due to intervening planets. In either case, we suggest that the ratio of warm/cool component temperatures is indicative of the scale of outer planetary systems, which typically span a factor of about 10 in radius.

Key words: circumstellar matter – infrared: stars.

1 INTRODUCTION

Debris discs are a sign of successful planetesimal formation. The radial structure of most planetesimal belts is unknown; they may lie in multiple rings analogous to the Asteroid and Edgeworth–Kuiper belts, but may also be significantly extended in a way similar to gaseous protoplanetary discs (e.g. Kalas, Graham & Clampin 2005; Su et al. 2009; Wyatt et al. 2012). Because they are generally detected by excess emission above the photospheric level at infrared (IR) wavelengths (e.g. Aumann et al. 1984), and with high-resolution imaging detections being relatively rare, discerning radial structure is in general difficult. The major difficulty is that the equilibrium temperature of a dust grain depends on both distance from the star and the size and optical properties of that dust grain. Thus, the radius of an unresolved debris disc cannot be unambiguously determined from the temperature of the observed emission, as the temperature is degenerate with the sizes of grains in the disc.

IR excess detections are generally well approximated by a single blackbody. This property is in part due to the emission properties of circumstellar dust, but also due to a lack of a high disc signal-to-noise ratio (S/N) over a wide range of wavelengths. However, an increasing number of more complex systems are being discovered with the help of mid-IR spectra, which when combined with far-IR photometry show emission at more than one temperature, and therefore may be indicative of dust that resides at a range of stellocentric distances (e.g. Backman et al. 2009; Chen et al. 2009; Morales et al. 2009; Ballering et al. 2013). Such discs can be modelled in different ways, but a promising approach is simply to add a second blackbody component (e.g. Chen et al. 2009, 2014; Morales et al. 2011; Ballering et al. 2013). These ‘two-temperature’ discs may be analogous to the Solar system, because a possible interpretation of two temperatures is an origin in dust emission from two distinct radial locations. Again by analogy with the Solar system, a further question is then whether the intervening region between the two belts contains planets, and if so, whether dynamical clearing by these planets is the reason for two-belt structure. Circumstantial evidence for such a picture is given by systems with planets that reside between two dust components, such as HR 8799 and HD 95086 (Marois et al. 2008; Reidemeister et al. 2009; Moór et al. 2013; Rameau et al. 2013).

An alternative interpretation is that the two belts may be linked by intervening planets, with material from an outer belt delivered to replenish the inner belt (e.g. Nesvorný et al. 2010; Bonsor & Wyatt 2012). From a study of many discs, Morales et al. (2011) concluded that the warmer of the two temperatures was typically

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∼190 K, regardless of whether the host star was Sun-like or an A type. They argue that the common warm dust temperatures may be a signature of sublimating comets passed in from outer regions, or asteroid belt analogues formed just interior to the system’s ‘snow line’.

Yet a third interpretation, where the two components are linked by grain dynamics (as opposed to planetesimal dynamics), relies on Poynting–Robertson (PR) drag (e.g. Burns, Lamy & Soter 1979). In this case, grains ‘leak’ inwards from the planetesimal belt, but are depleted by collisions with other grains as they drift inwards (Wyatt 2005; van Lieshout et al. 2014). A steady state is reached that balances the rates at which particles fill the region interior to the parent belt and are removed by collisions. This process does not lead to very large levels of dust inside the parent belt, but recent work coupled with increased mid-IR sensitivity has led to the conclusion that PR drag makes an important contribution in some systems (Reidemeister et al. 2011; Löhne et al. 2012; Schüppler et al. 2014).

Clearly, such interpretations present interesting possibilities for discerning planetary system structure and the dynamics of such systems. The origin and evolution of the putative warm components is of particular interest, since dust in the habitable zone may impact a future space mission to directly image and characterize exo-Earths (e.g. Beichman et al. 2006; Roberge et al. 2012). For example, Kennedy & Wyatt (2013) show how the known population of warm bright debris discs detected at 12 μm can be extrapolated to fainter levels by assuming that those discs are independent of any outer cool belts (i.e. evolve in situ). If the warm belts are replenished by comet delivery from elsewhere, such an extrapolation cannot be made.

Taking a step back however, the interpretation of two-temperature debris discs as physically extended or multiple discrete structures has only been tested in a few cases because it requires dedicated high-resolution observations. For example, η Tel shows what clearly appears to be a two-temperature disc spectrum (Fig. 1), but to confirm that the disc indeed comprises two distinct components has required high-resolution mid-IR observations (Smith et al. 2009a).

Therefore, our goal here is to consider a third model that could undermine work that assumes that a broad disc spectrum is always the result of extended or multiple disc components; namely that the debris may be confined to a relatively narrow belt and the breadth of the spectrum simply arises due to the absorption and emission properties of the dust (e.g. Matthews, Kalas & Wyatt 2007). It is well known that grains of different sizes can have different temperatures at a fixed stellocentric distance. It is also known that debris discs comprise not grains of a single size, but a distribution that extends from μm to at least cm sizes. Therefore, the specific question we wish to address here is whether two-temperature discs necessarily imply multiple dust components, or if their spectra can be reproduced by plausible grain populations residing in a narrow planetesimal belt. Though it is likely an important effect that contributes significantly in some cases, we do not consider PR drag here. We first compile a sample of two-temperature debris discs (Sections 2 and 3) and then discuss their properties (Section 4). We then consider whether these discs can be modelled as single belts (Section 5), and discuss the models and the origin of multiple belts (Section 6).

### 2 SAMPLE

This study was initially inspired by the presence of two-temperature discs among targets in the Herschel DEBRIS sample. These targets are outlined by Phillips et al. (2010), and comprise the nearest ~90 main-sequence stars of A, F, G, K, and M spectral types (i.e. ~90 of each type), excluding those near the Galactic plane. Not all DEBRIS sample stars were observed as part of our Herschel programme, some being observed by DUNES (Eiroa et al. 2013) and some as part of a guaranteed time programme (Sibthorpe et al. 2010; Vandenbussche et al. 2010; Acke et al. 2012). With only nine two-temperature sources in DEBRIS (as defined below), we expand the sample with more two-temperature discs observed by Spitzer (Werner et al. 2004). These were selected from a large data base of stars with Spitzer InfraRed Spectrograph (IRS; Houck et al. 2004) spectra and other mid/far-IR observations, mostly from IRAS and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) but also including Herschel and sub-mm photometry where available. The resulting sample has 48 robust two-temperature discs around stars with a range of spectral types (see Table A1). IRS spectra are almost always necessary for two temperatures to be detectable, so these observations set which stars are in our sample. Some sources were specifically targeted with IRS based on known excesses (e.g. from IRAS), so the sample for which two-temperature discs can realistically be detected is therefore biased.

Specifically, our sample includes stars from Morales et al. (2009), who selected known debris discs for observation by IRS based on the presence of 24 μm excesses. Morales et al. (2011) found that 46 per cent of these showed evidence for two temperatures. The discs in this sample are probably biased towards having two temperatures because the presence of a warm component adds extra 24 μm emission (e.g. Fig. 1). Similarly, some of our stars are from Chen et al. (2006), who observed a large sample of IRAS-discovered discs with 60 μm excesses, with IRS. Given that warm components are generally only visible at wavelengths shorter than 60 μm, objects observed in this programme are probably not biased towards two temperatures. However, as we demonstrate below, two temperatures are easier to detect when the overall disc fractional luminosity (f ≡ Ldisc/L emit) is greater, because the excess is detectable at a higher level than for discs with lower fractional luminosities.
S/N over a greater range of wavelengths. Thus, while the Chen et al. (2006) sample may not be biased towards discs having two temperatures, they are biased towards detection of two temperatures. These biases are in general unimportant for this study, though need to be considered for the statistics in Section 4.4.

For an analysis of a much larger sample of stars observed with IRS see Chen et al. (2014). Our sample is not meant to be complete, but to provide a sufficient number of sources for us to test whether the two-temperature discs arise from single or multiple belts. Our method for deriving the properties of two-temperature discs is different to Chen et al. (2014), though we arrive at the same broad trends.

### 3 SED MODELLING

Because a disc spectrum must be modelled at least once to determine whether multiple temperature components exist, sample selection is closely linked to spectral energy distribution (SED) modelling, which we now outline. For all systems, photometry ranging from optical to sub-mm wavelengths is compiled from a wide variety of sources, including all-sky surveys such as Hipparcos (Perryman & ESA 1997; Hog et al. 2000), 2MASS (Cutri et al. 2003), AKARI (Ishihara et al. 2010), WISE (Wright et al. 2010), and IRAS (Moshir et al. 1990). References for far-IR photometry are given in Table A1 and a compiled list of the (sub-)mm photometry is given in Table A2.

Data from the Spitzer mission is a crucial component, with IRS spectra needed in almost all cases to reveal two-temperature discs. These are generally obtained from the Cornell Atlas of Spitzer/IRS Sources (CASSIS) data base (Lebouteiller et al. 2011). However, the CASSIS data base only provides extractions for low-resolution staring-mode observations, and in some cases only high-resolution map-mode data were taken (e.g. HD 39060=β Pic). In these cases, or where previously published spectra were readily available (Chen et al. 2006, 2007, 2009; Su et al. 2013) we preferred these over the CASSIS extractions.

The IRS instrument is split into several modules, and the spectral extractions from the different modules must be aligned in relative terms to produce smooth self-consistent spectra. Previous works have generally aligned the modules simply using a handful of data in the region where the spectra overlap (e.g. Lawler et al. 2009; Chen et al. 2014). We took a slightly different approach, fitting the entire spectrum with a function and allowing the absolute values of all but one module (LL1) to vary as part of the fit, thus forcing the spectrum to be smooth across all modules and ensuring that any issues near the edges of each module did not strongly affect the results. For the fitted function, we used the sum of two power laws and one blackbody, the rationale being that the first power law accounts for the stellar Rayleigh–Jeans tail, and that the blackbody and second power law account for excess emission, which may look like either one of them or a combination of both (e.g. Morales et al. 2009, 2011). We found this method to work well and produce spectra comparable with previous methods.

Once aligned, the IRS spectra are split into seven photometric ‘bands’. Because the absolute value of the spectrum will not necessarily agree with other photometry (the absolute level varies at the ∼10 per cent level, e.g. Lawler et al. 2009), the spectrum is normalized so that the shortest band agrees with synthetic photometry of the best-fitting stellar photosphere model. The IRS bands are subsequently treated identically to other photometry. Because the quality of the spectral extractions vary, we found it necessary to add a 2 per cent systematic uncertainty to all spectra to avoid spurious excesses. In most cases this uncertainty dominates, so the formal uncertainty is larger than what would be expected from looking at the point to point scatter in the spectrum.

Photometry shortward of about 10 μm is used to model the stellar photospheric emission. This wavelength is varied from star to star depending on the temperature of the excess, ensuring both the best photospheric fit and that the excess does not affect this fit. For each star, the best-fitting model from a grid of PHOENIX AMES-Cond models (Brott & Hauschildt 2005) is found by a combination of brute force grids and least-squares fitting. For the few stars found to be over 10 000 K we use models from Castelli & Kurucz (2003), which span a wider range of effective temperatures. The remaining IR photometry is used to find the best-fitting disc model. We first subtracted synthetic photometry of the photosphere model from the observed fluxes to derive disc fluxes, with uncertainties derived from the photosphere and IR observation (including systematic uncertainties) added in quadrature. The disc parameters are then found via least-squares minimization, for which we use the modified blackbody,

\[ F_ν = n B_ν(T_{disc})X_1^{-1}, \]

where \( n \) sets the overall level of dust with temperature \( T_{disc} \), and

\[ X_1 = \begin{cases} 1 & \lambda < \lambda_0 \\ (\lambda/\lambda_0)^{\beta} & \lambda > \lambda_0 \end{cases}. \]

The blackbody function has units of Jy sr\(^{-1}\) so \( n \) is proportional to the surface area of dust in the disc. The fractional luminosity \( f_{disc} = L_{disc}/L_\star \) of a given disc is therefore proportional to \( n T_{disc}^4 \) (but also depends on \( X_1 \)).

The physical origin of this formalism comes from the inability of grains to emit efficiently at wavelengths longer than their physical size. Therefore, \( \lambda_0 \) is somehow related to grain sizes in the disc. It does not necessarily provide a direct measure of grain size however, because the observed emission comprises contributions from a size distribution of grains (which is related to \( \beta \)).

After fitting a single blackbody, each disc spectrum is inspected for goodness of fit. In most cases where it is necessary, the need for a second temperature component is clear. However, we found that a formal criterion (such as \( \chi^2 \)) can be a poor indicator because there can be other reasons for a poor model fit that are unrelated to the number of temperature components.

For example, ζ Lep shows evidence for extra emission above a blackbody around 10 μm (Fig. 2), which may be due to a silicate feature over the continuum, meaning that adding a second temperature component is not well justified based on the SED (mid-IR imaging suggests that the disc is somewhat extended; Moerchen et al. 2007). In some cases, the issue may be a discontinuity in the IRS spectrum near 15 μm, which is at the join between two different IRS modules and can cause a dip similar to that seen for ζ Lep (Chen et al. 2009). In general, we err on the side of caution and include the two-temperature discs that appear to be the most robust. The only targets in our sample with strong silicate features are β Pictoris and η Corvi, for which the presence of two temperatures is clear and corroborated by other studies (see end of this section).

While we could allow a separate \( \lambda_0 \) and \( \beta \) for the two components, these parameters are poorly constrained for the warmer component as the emission beyond the mid-IR is almost always dominated by the cooler component. We therefore fix \( \lambda_0 \) and \( \beta \) to be the same for both components, and there are six model parameters to fit.

For objects that we do model with two temperatures, there remain degeneracies between the six parameters that are not necessarily well described by the covariance matrix that results from...
the least-squares fitting. The most important is that disc temperature and normalization are strongly correlated at constant total disc luminosity by the Stefan–Boltzmann law. To estimate the parameters and their uncertainties in a more robust way we use an ensemble Markov chain Monte Carlo method (Goodman & Weare 2010)\(^1\) using \(e^{-x^2/2}\) as our likelihood function. Chains with an ensemble of 200 ‘walkers’ are initialized with parameters that vary randomly ±1 per cent from the \(\chi^2\) fitting results, and then run for 50 steps as a burn-in phase to eliminate any dependence on the initial state. This number of steps is sufficient to ensure that the initial conditions do not influence the results, being at least 10 times the autocorrelation length (Goodman & Weare 2010). The final distributions of parameters are created from a further 20 steps, resulting in 4000 samples from which we derive the probability distributions of each parameter.

Practically, rather than fitting the component temperatures individually, we fit the temperature and normalization of the cool component, and \(\lambda_0\) and \(\beta\) where sufficient photometry exists, and the ratio of warm to cool component temperatures

\[
R_T = T_{\text{warm}} / T_{\text{cool}}
\]  

(3)

and the ratio of warm to cool component normalizations \(R_n\). The ratio of fractional luminosities is

\[
R_f = f_{\text{warm}} / f_{\text{cool}}.
\]  

(4)

Here, \(R_T\) is the preferable quantity to work with because \(R_n\) and \(R_T\) are strongly correlated by the Stefan–Boltzmann law, but any reasonable fit must produce a disc with roughly the same luminosity. We derive values and uncertainties by fitting a Gaussian to the marginalized distributions for each parameter.

We retain two-temperature discs as those where the temperatures of the warm and cool components are significantly different (i.e. \(R_T > 3\sigma_R\)), and where the normalization of the warm component is significantly different than zero (i.e. \(R_n > 3\sigma_R\), all discs considered have significant cool components). The result of this process is a sample of 48 robust two-temperature debris discs. The targets are listed in Table A1 and the SEDs available in the online material. The overall fractional luminosities of these discs are shown in Fig. 3. Also shown are all discs for targets in the unbiased DEBRIS sample. The samples in this plot should not be used to conclude that two-temperature discs are typically brighter than other discs, or more common among bright discs, as significant biases exist among the two-temperature sample (see Section 2 for a discussion of sample statistics).

Among our sample we also note systems where observations with sufficient spatial resolution have been able to show that two distinct disc components exist. These systems are Vega and Fomalhaut (Su et al. 2013), \(\eta\) Crv (Wyatt et al. 2005; Smith, Wyatt & Haniff 2009b; Duchêne et al. 2014), HR 8799 (Su et al. 2009; Matthews et al. 2014), and \(\eta\) Telescopii (Smith et al. 2009a). We also include \(\beta\) Pictoris in this list, where the disc is seen to extend over a wide range of stellocentric radii (e.g. Smith & Terrile 1984; Telesco et al. 2005).

### 4 RESULTS

A simple way to present two-temperature discs is the ratio of temperatures \(R_T\) and fractional luminosities \(R_f\), as shown in Fig. 4. It is immediately clear that most two-temperature discs have fairly similar temperature ratios of 2–4, but with a range of fractional luminosity ratios. A clear outlier is \(\eta\) Crv, which has the largest temperature ratio, and is one of several systems known from detailed observations to have two physically distinct dust belts.

The source at intermediate \(R_T\) is HD 145689, which has an unconstrained cool component temperature and is therefore plotted as a lower limit in \(R_T\). It is not formally part of our final two-temperature disc sample, but is mentioned here as a potentially interesting two-temperature system found during our sample selection. As a probable outlier, we found it remarkable as the host of an M9 brown dwarf companion at 6.7 arcsec (Huelamo et al. 2013).
This source was proposed to be a ∼40 Myr old Argus star, and the disc model shown by Zuckerman et al. (2011) also has two-temperature components. At 52 pc (van Leeuwen 2007) the minimum companion separation is about 350 au. The disc radii implied by the two-temperature fit of about 200 and <35K are 7 and >180 au, respectively, though these are estimates assuming blackbody grains, the distances are probably ~3 times larger (Rodriguez & Zuckerman 2012; Booth et al. 2013). Therefore, if the 70 μm excess is associated with the star or companion, this system has three possible configurations (assuming that the larger than average temperature ratio is indeed indicative of multiple belts). The primary may have two well-separated belts and the companion either orbits between or beyond the two belts. The third possibility is that the cool dust component actually orbits the companion, but is heated by the primary. HD 145689 is clearly an intriguing system, having two components. Similarly, a warm component with a temperature approaching that of the star will be hard to detect photometrically (i.e. these are usually detected with interferometry), so stars with very large temperature ratios will also be hard to detect. Of course, sufficiently small temperature ratios will also be impossible to discern as comprising multiple temperatures. Combined, these criteria mean that there should be bounds on all sides of Fig. 4 that limit the range of two-temperature discs that can be discovered. The fainter the disc overall, the lower the S/N of all measurements will be in general, and therefore the less parameter space these bounds will cover.

To quantify this picture in a little more detail, Fig. 5 shows a simple approximation of the regions in which a ‘typical’ set of observations could detect two-temperature emission. At each point in the parameter space covered, we generated two pure blackbodies, with a fixed 70 K cool component, varying $R_T$ to set the warm component temperature, and then ‘observed’ them with synthetic photometry at seven IRS (4–35 μm), three MIPS (24–160 μm), and two Submillimetre Common User Bolometer Array (SCUBA, 450–850 μm) bands. We peak-normalized each total spectrum to unity, and estimated the uncertainties as 0.01$F^{1/2}$, which corresponds to 1 per cent uncertainty at the peak, and 32 per cent (i.e. a 3σ upper limit) for measurements two orders of magnitude fainter. We

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**Figure 4.** Two-temperature discs and uncertainties. The blue triangles note discs known to have multiple disc components from imaging and/or interferometry and the green diamond encloses HD 181327. The dot and arrow symbol marks HD 145689, host to an M9 companion, and for which $R_T$ is a lower limit (and $R_\eta$ an upper limit).

**Figure 5.** Simple model of sensitivity to two-temperature excesses, where light grey corresponds to greater sensitivity. Contours show $\chi^2$ from fitting a single temperature blackbody to two-temperature discs with the parameters at each point in the parameter space. Discs near the $\chi^2 = 1$ contour are well described by a single blackbody, and therefore two-temperature discs with these properties cannot be discovered given observations with typical S/N. The lowest $R_T$ and $R_\eta$ two-temperature discs lie near the edge of detectability, suggesting that discs with $R_T \lesssim 2$ and $R_\eta \lesssim 0.1$ do exist but were not detected here. Similarly, two-temperature discs near $R_T \sim 5$–6 and $R_\eta \sim 1$–10 are easily detected, so the gap between most discs and η Crv is real. Discs with $10 \lesssim R_\eta \lesssim 100$ and $R_T \gtrsim 2$ are detectable but were not seen, so must be rare.

**4.1 Sensitivity to two temperatures**

We now consider the sensitivity to two-temperature discs in the parameter space shown in Fig. 4. Clearly, discs whose components have very different levels of emission will be hard to identify as having two components. Similarly, a warm component with a temperature approaching that of the star will be hard to detect photometrically (i.e. these are usually detected with interferometry), so stars with very large temperature ratios will also be hard to detect. Of course, sufficiently small temperature ratios will also be impossible to discern as comprising multiple temperatures. Combined, these criteria mean that there should be bounds on all sides of Fig. 4 that limit the range of two-temperature discs that can be discovered. The fainter the disc overall, the lower the S/N of all measurements will be in general, and therefore the less parameter space these bounds will cover.
additionally set the minimum uncertainty to be 5 per cent. While this prescription simplifies the realities of photometry collected from different instruments with many different observing strategies, it represents the limits reasonably well (e.g. see Figs 1 and 2). To each spectrum, we fit a single blackbody and computed the sum of squared deviations per degree of freedom ($\chi^2_{red}$), which are the contours shown in Fig. 5.

In darker regions, where $\chi^2_{red}$ is low (i.e. $<1$) a single blackbody is a good model of the emission, and a two-temperature disc cannot be confidently detected. In lighter regions, where $\chi^2_{red}$ is higher, two-temperature discs are easier to detect. We have also shown the two-temperature discs from Fig. 4 (except HD 145689), which shows that the simple detection simulation is reasonable in the sense that no two-temperature discs lie where they should not be detectable. Fig. 5 shows that the most simple criterion for detecting two-temperature discs is that one component does not dominate over the other, and that their temperatures are not too similar.

Two-temperature discs are harder to detect in overall fainter discs, simply because their measurements are typically less precise. For the same photometric precision, lowering the overall disc brightness by a factor of 3 results in uncertainties that are three times larger. In Fig. 5, the $\chi^2_{red}$ contours would therefore be divided by a factor of 9 and discs with $R_f$ lower than about 0.2 become harder to detect.

We return to the effect of this disc luminosity bias when looking at spectral type trends below.

Our simulation does not include a limit at large temperature ratios because these are limited not by the disc properties, but by difficulties in distinguishing the warm component from the star. Because discs are rarely cooler than $\sim 30$ K, and discs hotter than $\sim 500$ K become increasingly difficult to detect with photometry, the practical upper limit on detectable temperature ratios is in the 15–20 range (depending on the temperature of the cool component).

The conclusions from this analysis are (i) that the lowest $R_f$ and $R_T$ discs lie near the sensitivity limits, meaning that discs with lower $R_f$ and $R_T$ probably exist, but were not detectable here, (ii) that two-temperature discs are harder to detect when the overall disc luminosity is lower, (iii) that discs with $10 \lesssim R_f \lesssim 100$ and $R_T \gtrsim 2$ are detectable but were not seen, so must be rare, and (iv) the gap between most discs and $\eta$ Crv is in a region where two-temperature discs are most easily detected, so the gap is real and the $\eta$ Crv disc is a rare outlier among two-temperature discs.

4.2 Trends with spectral type

Fig. 6 shows how some of the derived disc parameters vary with stellar effective temperature, as well as approximate biases due to
the sensitivity to two temperatures described above. Chen et al. (2014) analysed a much larger sample of stars observed with IRS, and found similar trends, though they did not present the results in terms of the ratios we use here.

The temperature of the cool component increases with $T_{\text{eff}}$, as might be expected due to increasing stellar luminosity if all discs have similar characteristic sizes (see Ballering et al. 2013, for further discussion of this trend). Because $R_f$ is generally similar for all stars, the warm component temperatures show the same trend. This conclusion is in contrast to Morales et al. (2011), who found that the warm component temperature was generally constant, regardless of spectral type (also see Chen et al. 2014). However, plotting their temperatures shows a probable correlation, with all Sun-like stars having warm components < 220 K, but 15 out of 24 A-type stars having warm components > 220 K. Indeed, their A-type sample contains stars that range from B8 to A7 and there is also a trend among these for the hotter stars to have warmer warm excesses. A possible bias exists here however, because for fixed sensitivity to $R_f$, increasing cool belt temperatures mean that only warm belts with increased temperatures can be detected. A predicted detection line of $R_f \gtrsim 2$ is shown in the lower-left panel of Fig. 6, based on the lower envelope of temperatures in the lower-right panel. The lowest warm temperatures around the hottest stars lie farther above the detection line than would be expected, so it seems likely that the trend towards warmer warm belts around hotter stars is real. There is no such bias for the top envelope of points in any of the panels, so the observed increase in the warmest warm component temperatures with stellar temperature also argues that the trend is real. Our interpretation of both sets of two-temperature fitting results is therefore different to the Morales et al. (2011) conclusion of common warm dust temperatures, instead finding a probable trend for warmer dust around hotter stars.

While the maximum $R_f$ appears to be constant, the minimum $R_f$ appears to increase with $T_{\text{eff}}$, and the hottest stars tend to have similarly luminous warm and cool components. This trend may be a bias however, as the hotter stars in our sample tend to have lower overall fractional luminosities (Fig. 3), for which detecting low $R_f$ discs is more difficult (as indicated by the dotted line in the upper-right panel).

### 4.3 Discs with single temperature spectra

As we have emphasized, to be sure that a debris disc comprises multiple components requires at least one of those components to be resolved. For example, discs with well-resolved outer belts such as Fomalhaut and Vega show unresolved emission closer to the star at $\sim 10$ au, which is strong evidence for multiple belts that in these cases is consistent with their two-temperature SEDs (Su et al. 2013).

There are however, also discs that show both warm and cool emission from imaging but appear to have single temperature disc spectra. For example, $\alpha$ CrB is resolved in both mid-IR and far-IR imaging, suggesting that the disc has either two belts, or a disc that extends over a wide range of radii, yet the SED is well fitted by a single modified blackbody (Moerchen, Telesco & Packham 2010; Kennedy et al. 2012). An intermediate class also exists, where the disc spectra are sufficiently complicated by spectral features that a poor single temperature fit does not immediately suggest that a two-temperature model would be better (e.g. Fig. 2). As another example, the HD 113766A disc spectrum can be modelled moderately well as a single component, but when considered in light of mid-IR interferometry, the combined photometry shows that a two-belt model is a better interpretation (Olofsson et al. 2013).

An additional question is whether there are discs where two-temperature behaviour was not detected where it could have been, or stated another way; do all discs have two temperatures? While it does not have two temperatures, a disc such as that around HD 113766A is not particularly well suited for this test because it has strong spectral features. Two that are well suited are HD 191089 and HR 4796A, as shown in Fig. 7. Both discs are extremely bright ($f = 0.001–0.006$) and the high S/N are very well modelled by modified blackbodies at about 100 K. From the range of $R_f$ and $R_f$ at the effective temperatures of 6500 and 8630 K, Fig. 6 shows that a typical warm component would have $T_{\text{warm}} = 200–400$ K and $f = 10^{-4}$ to $10^{-2}$, which would have been easily detected. Fig. 5 suggests that warm discs in this temperature range would still be detectable if they were up to an order of magnitude fainter.

Churcher, Wyatt & Smith (2011) concluded from mid-IR imaging that the inner regions around HD 191089 are truly depleted,
suggesting that in addition to appearing as a single temperature disc, that the emission does actually come from a single belt. Our result of a single temperature is in contrast to the two-temperature model of Chen et al. (2014), which they strongly prefer. However, this appears to be an artefact of their analysis, which decreases the MIPS 70 μm uncertainties by a factor of 70. Our inclusion of longer wavelength photometry shows that the second temperature component is not justified.

Detailed modelling of HR 4796A requires two spatially distinct dust belts (Augereau et al. 1999; Wahhaj et al. 2005). Again our model is in disagreement with Chen et al. (2014), who find a warm temperature component at 231 K. The main difference between our methods is that we tie our IRS spectra to the photosphere, whereas Chen et al. (2014) tie it to MIPS 24 μm photometry, which requires an accurate relative calibration between the photosphere models and MIPS data. Inspection of the distribution of 13 and 24 μm observed/star flux ratios from their table 2 provides a possible resolution; near unity their distributions have means of 1.02 and 1.03, respectively, suggesting that the photospheres are on average underestimated relative to IRS. A possible origin of this discrepancy is that the 2MASS photometric system is about 2 per cent fainter than that used by MIPS (Rieke et al. 2008), which if not corrected for will lead to slightly fainter photospheres and the inference of warm disc components where the evidence is marginal.

Chen et al. (2014) find that there are many other examples of single temperature discs. Therefore, not all stars have strong evidence for two-temperature discs even when they could have been detected, and single temperature discs may or may not actually have multiple belts.

4.4 Statistics

Given that many two-temperature discs are known to exist, it is desirable to make an estimate of how common the phenomenon is. Ultimately, we are biased by the overall set of stars that were observed with IRS, since among nearby stars these were typically those already known to host bright discs, and we are therefore biased towards detecting two-temperatures in general. This bias means that any simple estimate of the two-temperature occurrence rate will very likely be an overestimate.

We first consider stars in the unbiased DEBRIS sample (i.e. including stars observed by DUNES and with guaranteed time). Only one of these was observed by the Morales et al. (2009) programme (HD 110411), meaning that objects in this sample observed with IRS are unlikely to be strongly biased towards having two temperatures (see Section 2). Our sample of two-temperature discs has nine DEBRIS stars (six A type, two F type, and one K type), while the DEBRIS sample itself has 83 A-type, 94 F-type, 89 G-type, 91 K-type, and 89 M-type primary stars. Of these, 21, 17, 9, 6, and 1 were observed with IRS and have detected discs, respectively, meaning that the raw fractions of discs that have two-temperatures are 6/21, 2/17, 0/9, 1/6, and 0/1.

Fig. 3 shows how our overall sample of two-temperature discs compares to the DEBRIS sample. The volume-limited DEBRIS sample includes relatively few bright discs (as these are rare), and only the brightest DEBRIS discs are seen to have two temperatures. However, the fainter discs may have two-temperature components that could not be detected. A lack of sensitivity may therefore account for only a few (3/32) two-temperature discs among FGK stars in DEBRIS. With the above caveat about a bias towards two temperatures among IRS-observed discs, this fraction suggests that two-temperature discs are fairly common around FGK stars. For A types, there is still little overlap in the two-temperature and DEBRIS stars in Fig. 3, but nearly 30 per cent of A-star discs are seen to have two temperatures. Further, Fig. 6 shows that these discs tend to have higher $R_e/s$, meaning that it is likely that some of the remaining 70 per cent of DEBRIS A-type discs should have detectable two-temperature behaviour that was not seen. Therefore, this largely qualitative look at two-temperature discs among DEBRIS stars suggests that the phenomenon could be relatively common, at a level of a few tens of per cent.

To approach this issue from another angle, we consider the brightest discs observed with IRS by Chen et al. (2006), those with overall fractional luminosities above $10^{-3}$. These six discs are all around stars younger than ~20 Myr old, and are sufficiently bright that two-temperature discs similar to others in our sample should have been easily detectable. These are HD 95086, HD 110058, HD 113766, HD 146897, HD 181327, and HD 191089. Of these, HD 95086 and HD 181327 show two temperatures (Lebreton et al. 2012; Mörk et al. 2013), while the other four do not. HD 113766 has a silicate feature that makes SED fitting complex, but is inferred to have two spatially distinct components (Olofsson et al. 2013). Therefore, one third of this small number of stars with discs show two temperatures.

This rough estimate is lower than the 66 per cent found by Chen et al. (2014), and in closer agreement with 46 and 33 per cent found by Morales et al. (2011) and Ballering et al. (2013). There seem to be three possible reasons for this difference. The first two are related to the way Chen et al. (2014) model their disc spectra, which may result in detection of more two-temperature discs as described above in relation to HD 191089 and HR 4796A. A third possible reason is the difference in samples, because Chen et al. (2014) include many young stars. They found that younger systems are more likely to have two-temperature discs, which may increase their detection rate of two-temperature discs, particularly if many of these young stars were observed based on previous disc detections.

Another question is therefore whether the frequency of two-temperature discs changes with age, or whether they are just easier to detect due to brighter discs at younger ages. For example, if the warm components are related to ongoing terrestrial planet formation and are independent of the outer cool components, then two-temperature discs would only be expected to appear around stars younger than ~100 Myr. We can therefore compare our rough two-temperature occurrence rates from DEBRIS and the younger Chen et al. (2006) sample. Though our power to distinguish them is limited, there is no evidence among these samples that the fraction of two-temperature discs changes with age. Though they did not consider this possibility, fig. 9 from Chen et al. (2014) suggests that the frequency of two-temperature discs is generally fairly constant, but could be higher for systems younger than ~10 Myr. We consider this issue in more detail in Section 6.2.

To summarize, the results do not rule out two-temperature behaviour for most discs, because most are too faint for it to be detected reliably. We have also shown that there are examples of single temperature discs where two temperatures could have been detected. Based on this discussion it seems that two-temperature discs are certainly not rare, but neither are they ubiquitous.
which we consider first. We then move on to numerical models, whose spectra in general depend on the host star, the grain size distribution, and the optical properties of the grains.

5.1 Grain temperatures

Fundamentally, two-temperature emission could arise from single dust belts because the temperature of dust grains depends on their size, as shown in Fig. 8. There are two temperature regimes separated by a transition region; the cooler blackbody regime is where grains are large and absorb and emit efficiently at all wavelengths, and the ‘small’ regime is where grains absorb and emit inefficiently at all wavelengths. The exact location of these regimes depends on the spectral type of the star and the radial location of the dust, but is a fairly weak function of these parameters. Fig. 8 shows that while the temperatures vary considerably with spectral type and radial distance, the ratio of temperatures in the small (\(T_{sm}\)) and blackbody (\(T_{BB}\)) grain regimes is fairly constant at around 2–3.

To understand this ratio theoretically we balance the energy absorbed by a dust particle of diameter \(D\) over area \(\pi D^2/4\) and emitted from an area \(\pi D^2\) at stellocentric distance \(r\)

\[
\frac{R^2}{4r^2} \int_0^\infty Q_{abs} B_\nu(T_\nu) \, d\nu = \int_0^\infty Q_{abs} B_\nu(T_{dust}) \, d\nu.
\]

For a blackbody particle that is perfectly absorbing and emitting \(Q_{abs} = 1\) and the blackbody dust temperature is

\[
T_{BB} = \frac{T^4}{4r^2} = \frac{L_*}{16\pi\sigma_{SB}r^2},
\]

where \(\sigma_{SB}\) is the Stefan–Boltzmann constant.

If we now consider a grain that is small relative to the peak wavelengths of star and disc emission, the absorption and emission efficiency is \(Q_{abs} \propto \lambda^{-n}\) at wavelengths that contribute significantly to the integrals in equation (5). For fixed \(n\) these integrals are \(\propto T^{4+n}\), so equation (5) can be rewritten as

\[
\frac{T_{sm}}{T_{BB}} = \left(\frac{T_*}{T_{BB}}\right)^{(n/4+n)}.
\]

For typical values of \(n = 1–2\) (e.g. Helou 1989), \(T_* = 6000\) K, and \(T_{BB} = 70\) K, equation (7) yields \(T_{sm}/T_{BB} = 2.4–4.4\), which is in good agreement with the ratios found in Fig. 8.

Figure 8. Grain temperatures as a function of diameter for dust around A-, G-, and M-type stars at 10 and 100 au. The temperature ratios for small and large grains in this figure vary from 2.2 to 3.3. The grain model is described in Section 5.2.1.

Figure 9. \(R_T\) as a function of \(r_{cool}\). A weak positive correlation is predicted by equation (7), shown for A0V and G0V stars for \(n = 1\) and 2.

These values are therefore representative of the temperature ratios \(R_T\) that are achievable in a two-temperature debris disc with dust in a single belt. While the observed ratios could be smaller, if for example the smallest grains present in the disc were \(\sim 10\) \(\mu m\) in size and therefore grains of \(T_{sm}\) non-existent, they cannot be larger than allowed by the grain properties. If we take \(T_{sm}/T_{BB} = 5\) as an approximate maximum allowed value, then \(\eta\) Crv with \(R_T = 6.4\) is the only source for which the conclusion of two spatially distinct belts would be well founded based purely on these simple temperature considerations.

Equation (7) also predicts a weakly increasing temperature ratio with disc radius (via \(T_{BB} \propto \sqrt{r}\)). Fig. 9 shows \(R_T\) against disc radius in search of this trend, with lines showing the predicted correlation. No clear trend is visible, and the scatter in the points is larger than the variation expected for \(n = 1\). The expected trend for \(n = 2\) is larger, but as comparison with Fig. 8 shows, \(n = 2\) tends to overestimate values for \(R_T\) so is probably too extreme to be representative. Inspection of this plot as a function of spectral type shows no trends, though the relatively small difference between lines of different spectral types shows that the expected differences are small. Therefore, this comparison shows that a possible \(R_T\) dependence on \(r_{cool}\) is not a good diagnostic of two-temperature discs that may arise from the range of grain temperatures in a single belt.

There is one more important aspect to be explored before turning to a more complex model, which is the minimum grain size. The conclusion that any disc with \(R_T \lesssim 5\) can be produced by a single dust belt relies on grains smaller than \(\sim 1\) \(\mu m\) being able to survive in the disc. However, it is thought that such small grains are blown out by radiation pressure on dynamical time-scales for Sun-like and earlier type stars. Adopting the relation for the blowout size in microns

\[
D_{bl} = 0.8(L_*/M_*)(2700/\rho),
\]

where \(\rho\) is density in kg m\(^{-3}\) and the luminosity and mass are in solar units, implies that while Sun-like stars can retain grains that are small enough to achieve \(T_{sm}\), AO-type stars with typical blowout sizes of 10 \(\mu m\) do not. Therefore, a conclusion from Fig. 8 is that early A-type stars only retain grains that are all roughly the temperature of a blackbody. Therefore, if the calculated blowout size is representative of the minimum grain size, early A-type stars
Numerical models

Having considered the possible range of grain temperatures, we now consider what is probable given realistic size distributions and compositions. The size distribution can be reasonably approximated by a power law with a single slope parameter, while the optical properties require a handful of parameters that describe the material composition.

5.2.1 Model description

In what follows, we use a fairly standard grain composition model (Augereau et al. 1999). In this model, all grains have the same basic properties, and are a mix of crystalline/amorphous silicates and organics with some assumed porosity, where the vacuum arising due to the porosity can be filled to some degree with crystalline or amorphous water ice. Grain properties are calculated using Mie or Rayleigh–Gans theory or geometric optics in the appropriate regimes (Laor & Draine 1993), using optical properties derived by Li & Greenberg (1997, 1998). The refractive indices of each material are mixed according to Maxwell–Garnett effective-medium theory, which is not the only choice, but was preferred because it allows the grains to be treated as a silicate core with a mantle of organics (i.e. the components are not treated equally when mixed). This grain model is not the only possible approach, and for example has problems reproducing observations when confronted with debris discs observed both in thermal and scattered light (e.g. Krist et al. 2010; Acke et al. 2012). However, it has succeeded in many instances when modelling of mid- to far-IR disc spectra was required (e.g. Augereau et al. 1999; Wyatt & Dent 2002; Lebreton et al. 2012), and provides a unified approach that has proven a useful tool for creating models more realistic and complex than simple blackbodies.

Even with the various assumptions that were made in creating this grain model, there are several more to be made. As outlined above, the minimum grain size and the size distribution are important in setting the disc spectrum. We must also specify the mixture of silicates, organics, vacuum (via porosity), and water ice (if the porosity is non-zero), and whether these are crystalline or not. Formally, $q_{\text{si}}$ sets the fraction of total silicate+organic volume occupied by silicates, $p$ the porosity fraction, and $q_{\text{H}_2\text{O}}$ the fraction of vacuum filled with ice. We set the blowout size as the size at which the radiation to gravitational force ratio parameter $\beta$ is 0.5.

For the composition, we use two different models that illustrate how the disc spectra can vary. While previous authors (e.g. Augereau et al. 1999) have used compositions at different extremes of what is possible, for example interstellar medium-like and comet-like, to explore how disc spectra can vary, we found that crystalline comet-like compositions produced discs with strong spectral features that are not seen among our sample. Our two compositions are therefore not so extreme. We default to moderately porous grains with 1/3 amorphous silicates and 2/3 organics, and a small amount of water ice (i.e. $p = 0.5$, $q_{\text{si}} = 1/3$, $q_{\text{H}_2\text{O}} = 0.05$), which we call our ‘rocky’ composition. For a second model, we increase $q_{\text{H}_2\text{O}}$ to 0.85, which we call the ‘icy’ composition.

Above, we considered the possible range of temperatures that could be present in a dust belt. However, how different sizes contribute to the overall emission is set by the size distribution, so unless it allows both the coolest and warmest grains to contribute roughly equally to the emission, the presence of multiple dust temperatures will not result in a two-temperature disc spectrum. One common way of describing the number of objects between diameters $D$ and $D + dD$ in the size distribution is

$$n(D)dD = KD^{-3q}dD,$$

(9)

where $K$ sets the normalization and $q$ the steepness of the distribution (the origin of $q$ being in the mass distribution $n(M)dM \propto M^{-3q}(dM)$. When $q > 1.67$, the surface area is dominated by the smallest particles. A standard value for $q$ under the assumption of an infinite size distribution with strength-independent size is 1.83 (Dohmannyi 1969). However, the slope $q$ varies depending on the size-dependent strength of objects (O’Brien & Greenberg 2003), with typical values expected to be around 1.8–1.9 for objects that dominate the observable emission (e.g. Gáspár et al. 2012).

5.2.2 Model results

We now show disc spectra for single belt models with a range of size distributions and our two compositions. We first show why changing the size distribution has important consequences for the disc spectrum, and then how these models compare to the observed sample of two-temperature discs for a range of size distributions and our two compositions.

We begin this part of the analysis with Fig. 10, which shows a typical disc spectrum using the ‘rocky’ composition with $q = 1.9$ at 100 au from a Sun-like star with the solid black line. The resulting spectrum is well matched by a modified blackbody beyond 20 μm (dashed line). No two-temperature behaviour is present and if anything, the blackbody model has too much warm emission rather than too little. What is also clearly visible is that the emission is made up of a range of temperature components (grey lines), to the extent that it is perhaps remarkable that the overall spectrum is well described by a modified blackbody. The size distribution of $q = 1.9$ means that the spectrum contains a reasonable balance of these

![Figure 10. Disc spectrum for $r = 100$ au around a Sun-like star with our ‘rocky’ composition and $q = 1.9$, $D_{\text{bl}} = 3$ μm. The maximum object size is 1 km. The solid black line shows the total spectrum, solid grey lines show the contribution from 15 logarithmically spaced size bins (from 3 μm to 40 mm with a factor of 1.96 spacing). Pebbles larger than 40 mm lie off the bottom of the plot. The dashed line shows a 106K blackbody with $\lambda_0 = 123$ μm and $\beta = 0.88$.](https://academic.oup.com/mnras/article-abstract/444/4/3164/1021189)
temperature components and the overall spectrum has a temperature that is somewhere between $T_{\text{sm}}$ and $T_{\text{BB}}$.

To create a disc spectrum that looks more like it has two temperatures will require different relative numbers of small and large grains. Decreasing the contribution from large grains will only push the spectrum further towards something that looks like a modified blackbody at $T_{\text{sm}}$. However, increasing the number of large grains can result in a more even contribution and a broader spectrum, as shown in Fig. 11. This figure shows the result if $q = 1.73$, which clearly shows a two-temperature spectrum. The two-blackbody fit has $R_T = 2.6$ and $R_f = 1.8$, which lies amongst the discs shown in Fig. 4, though with a relatively high $R_f$. Some experimentation shows that two-temperatures are required to fit our grain model SEDs for Sun-like stars when $q \lesssim 1.8$, and that similar results can be obtained using either our rocky or icy compositions. As noted above, this scenario does not work for early A-type stars, as long as we retain the assumption that subblowout size grains do not make a significant contribution to the disc spectrum.

To illustrate the range of behaviour and the trends that arise from these relatively steep size distributions, Fig. 12 shows models with our rocky composition ($q_{\text{H}_2\text{O}} = 0.05$) for a range of size

![Figure 11](image1)

**Figure 11.** Same as Fig. 10, but with $q = 1.73$. The model has temperatures of 36 and 86 (dotted lines, with $R_T = 2.6$) and $R_f = 1.8$, with $\lambda_0 = 206\,\mu$m and $\beta = 0.35$. The flatter size distribution means that large objects, even those with 1 km diameters, contribute significantly to the overall spectrum.

![Figure 12](image2)

**Figure 12.** Example two-temperature disc spectra for a range of spectral types and size distribution slopes (noted in the top left of each panel), assuming that the minimum grain size is the blowout size and with our ‘rocky’ composition ($q_{\text{H}_2\text{O}} = 0.05$). All discs are at 100 au. Each panel shows the contribution of grains of different sizes (grey lines) and the total spectrum (solid line). The best-fitting two-temperature blackbody model is shown (dotted line), as is each component (dashed lines). The synthetic photometry used to fit the model is shown as squares. Each legend shows the disc temperatures, best fit $\chi^2$, $\lambda_0$, $\beta$, $R_T$, and $R_f$.

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Figure 13. Sample of two-temperature debris discs (same as the top panels of Fig. 6), with additional lines showing parameter space covered by the models from size distribution models from Fig. 12 and Section 5.2.2. The two different sets of lines show the ‘rocky’ and ‘icy’ compositions we considered. Each vertex represents a model that resulted in a two-temperature disc. The vertical solid lines connect models at constant $T_{\text{eff}}$ and near-horizontal dashed lines connect models of constant $q$ (with values of 1.68, 1.72, 1.77, and 1.82 as shown in Fig. 12). The main trends are that earlier spectral types have lower $R_T$, and smaller $q$ results in lower $R_f$.

distributions ($q = 1.68, 1.72, 1.77, \text{ and } 1.82$) and spectral types (A5, F0, G0, and K0) with fitted blackbody models. We use the same assumptions for fitting blackbody models as in Fig. 5, but now fit two-temperature components. The second fitted component is not shown if it has the same parameters as the first. Some trends are clear; $R_f$ tends to increase with the steepness of the size distribution, which can be understood simply as a result of the decreasing contribution of the large grains. The typical $R_T$ increases to later spectral types, which is the result of smaller blowout sizes and therefore a wider range of grain temperatures (e.g. Fig. 8).

Fig. 13 shows the temperature and fractional luminosity ratios against stellar temperature for our observed sample (i.e. the same as the top panels of Fig. 6), with the addition of the range of parameters found from the grid of ‘rocky’ composition models in Fig. 12 plotted as red lines. Each vertex corresponds to a model that required a two-temperature blackbody fit. For these grids, vertical solid lines show the effect of varying the size distribution slope $q$ at constant spectral type, and near-horizontal dashed lines show the effect of varying the spectral type at constant size distribution slope. The trends described above for Fig. 12 are apparent; models with flatter size distributions tend to have lower $R_f$, and $R_T$ generally decreases as stellar effective temperature increases but depends only weakly on $q$. For this composition, the models have lower $R_T$ than most observed discs, and only reproduce the discs with higher $R_f$.

We now introduce the second ‘icy’ composition ($q_{\text{H}_2\text{O}} = 0.85$), plotted as blue lines in Fig. 13. These models have been calculated over the same grid of size distribution slopes and spectral types. A set of SEDs analogous to those in Fig. 12 looks qualitatively similar, and shows the same trends. This icier composition covers a somewhat different range of $R_T$ and $R_f$, resulting in two-temperature discs with lower values of both ratios. The effect of changing $q$ gives a similar change as the difference between the two different compositions in logarithmic $R_f$, suggesting that these can be equally important effects. In general however, flatter size distributions are required to reproduce the lowest observed values of $R_f$.

Both models have trouble producing $R_T$ as large as those observed, particularly for earlier spectral types due to larger blowout sizes.

For the few models where $R_T$ is in reasonable agreement, $R_f$ is relatively high ($\gtrsim 1$).

To emphasize the $R_T$ versus $R_f$ parameter space covered, Fig. 14 shows the model grids compared to our two-temperature sample. As is expected from the variations in Fig. 13, the models do not cover this space in a simple linear fashion, but do show that only discs with relatively low $R_T$ are reproduced by narrow belt models. At low $R_f$, model discs with $R_T$ larger than about 2 are not seen, increasing to about 3 at higher $R_f$.

As noted above, the main conclusion from Fig. 13 is that $R_T$ decreases to more luminous stars; their blowout sizes increase with luminosity and they do not show two-temperature spectra for spectral types earlier than about A5. Based on the overlap between

Figure 14. Sample of two-temperature debris discs (same as Fig. 4), with lines showing parameter space covered by the models from size distribution models from Fig. 12 and Section 5.2.2. The two different sets of lines show the ‘rocky’ and ‘icy’ compositions we considered. Each vertex represents a model that resulted in a two-temperature disc. The solid lines connect models at constant $T_{\text{eff}}$ and dashed lines connect models of constant $q$. 
the observed two-temperature and model discs in Figs 13 and 14. Sun-like stars with relatively small $R_T$ may be described by our single belt model. The single belt system HD 181327 lies within our model grids with a range of size distributions depending on the composition ($q \approx 1.67–1.82$) compared to the results of Lebreton et al. (2012), who found $q \approx 1.8$ but used a carefully tuned mix of three material components. That such complex single belt models can be successfully constructed in individual cases suggests that our two simple models can be taken as a general indication of where plausible models lie. This parameter space can no doubt be expanded somewhat with more complex prescriptions. We return to tests of this single belt model below.

6 DISCUSSION

In the preceding sections, we have shown the properties of a sample of two-temperature debris discs. These discs typically have warm/cool component temperature ratios $R_T$ of 2–4, and warm/cool component fractional luminosity ratios $R_V$ below 10 (Fig. 4). Warm components are detected with $R_V$ down to about 0.1, and those fainter than this level become difficult to detect (Fig. 5). Biases in the sample mean that the frequency of the two-temperature phenomenon is hard to estimate, but it appears fairly common, at the tens of per cent level.

We then explored how two-temperature disc spectra may arise from narrow planetesimal belts, rather than two distinct belts as is generally assumed. The motivation comes from the known variation of dust temperature with size (Fig. 8), and the possibility that a single belt with properly modelled grain emission might provide a simpler explanation for two-temperature discs than the assumption of multiple belts. We found that a single belt can appear to have two temperatures, but that the specific parameters depend on the size distribution and grain composition assumed. A weakness of this model is that the maximum $R_T$ produced is 2–3, smaller than seen for many systems. In addition, the single belt model only works for discs around Sun-like stars, because more luminous stars remove small grains via radiation forces, and the range of grain temperatures across the size distribution is then smaller than observed.

6.1 Testing the single belt model

The single belt scenario ultimately relies on the range of temperatures that grains can have at a single stellocentric distance, which range from those of blackbodies at $T_{BB}$, to those of very small grains at $T_{ins}$. To reproduce the low $R_V$ values seen for some systems requires relatively flat size distributions, where the two-temperature components correspond to these extremes, and in particular the cool component is dominated by emission from objects that behave like blackbodies. A prediction of this scenario is therefore that the true radius of the belt should correspond to that predicted by the blackbody temperature of the cool component, which can be tested in cases where two-temperature discs have been spatially resolved. For example, Morales et al. (2013) found for four two-temperature discs that the resolved size was two to three times larger than that predicted by a blackbody. Similar conclusions were reached by Booth et al. (2013) for two resolved discs. Therefore, comparison of predicted and resolved disc sizes does not appear to support the single belt scenario when relatively flat size distributions are required. However, most debris discs are not resolved, so this test is inconclusive in general.

In cases where the cool belts are cool enough for the predicted blackbody size to be in rough agreement with the resolved size, or where the resolved size is unknown, an alternative test can be made. If the cool component is dominated by emission from grains at the blackbody temperature, then the spectral slope of the far-IR and mm emission should also appear similar to a blackbody (i.e. $\beta \approx 0$). This property can be seen in Fig. 12, where $\beta$ is closer to zero for discs with flatter size distributions (left-hand column). In these spectra, $\beta$ does not reach zero because the cool component contains some emission from grains large enough to have near-blackbody temperatures, but small enough to emit inefficiently at sub-mm wavelengths.

To illustrate this point, Fig. 15 shows two-temperature discs from our sample where $\beta$ is constrained, which includes a range of host spectral types. The plot also includes the grids of models described in Section 5.2.2. The size distribution slope $q$ affects both $\beta$ and $R_V$, so this plot tests whether the $\beta$ predicted for a given $R_V$ is similar to that observed. The models are again shown as lines of constant $T_{eff}$ (solid) and $q$ (dashed), and as in Fig. 14 the models do not cover this space in a simple linear fashion. Overall however, these models predict lower $\beta$ for lower $R_V$, and for the compositions used here consistently lie below the observed discs, with the exception of η Crv, which lies below the models. Different or more complex grain models could be consistent with discs that lie near the model lines, with HD 181327 being a specific example. Overall however, the single belt model again appears inconsistent with the observed disc properties in the few cases where it can be tested. This test can only be made for relatively few discs because sufficiently sensitive observations at far-IR/mm wavelengths are required, and these are difficult to obtain. This difficulty leads to a bias, in that discs with lower $\beta$ are more easily detected at long wavelengths (i.e. those closer to pure blackbodies), and strengthens the conclusion that the observed two-temperature discs have larger $\beta$ than expected from the single belt model.

Discs that lie close to HD 181327 in Fig. 15 may be the best place to look for two-temperature discs arising from single belts. The four
lying along a locus with similar slope to the models are HD 39060 (β Pic), HD 32297, HD 110411 (ρ Vir), and HD 161868 (γ Oph). Of these, β Pic has a well-studied and complex disc structure, that extends over a range of radii (e.g. Smith & Terrile 1984; Telesco et al. 2005; Dent et al. 2014). HD 32297 was modelled as two belts by Donaldson et al. (2013), and while they find that the inner component could not be accounted for by their models of the outer component, this putative inner component has yet to be confirmed. HD 110411 and HD 161868 have relatively little spatial disc information and no resolved detection of an inner component (Moerchen et al. 2010; Booth et al. 2013). Therefore, three of these four discs represent worthy targets for future high-resolution imaging that test for the presence of inner disc components.

In summary, our models show that in some cases two-temperature discs do arise from single belts. As long as the minimum grain size is set by radiation pressure, two-temperature discs around A-type stars probably arise from multiple belts. In addition, a few two-temperature discs have been confirmed to have multiple belts by high-resolution observations, and these comprise both A-type and Sun-like stars. For Sun-like stars, single belt models, particularly those with relatively flat size distributions, can produce two-temperature discs, and this model is not conclusively ruled out because not all discs are resolved and/or detected at far-IR/mm wavelengths. Where observations exist however, this model is disfavoured. In addition, the flatter size distributions are steeper than those expected from collisional models and inferred from detailed modelling of well-characterized systems. Therefore, in general, the assumption that two-temperature discs have multiple belts should not be made without considering the properties of those discs and their host stars, but it seems likely that the bulk of two-temperature discs do arise from multiple belts.

6.2 Evolution of multiple belts

We now consider whether our results shed light on the origin of multiple belts, which in general appear to be the origin of two-temperature discs. A possible constraint could come from the expected collisional evolution. For example, if two-temperature discs arise from a single belt and the material compositions do not change, no significant evolution of $R_\text{f}$ or $R_\text{f}$ would be expected over time because the observed emission always comes from material in the same location. However, this similarity may also be expected if the warm belts are made of material delivered from the outer belt, perhaps scattered by planets (e.g. Wyatt et al. 2007; Bonsor & Wyatt 2012), in which case the brightness of the inner belt is reasonably connected to that of the outer one.

On the other hand, if two temperatures arise from two independent belts (i.e. as in the Solar system), the two belts are expected to collisionally evolve at different rates. We can estimate the results of differential evolution by assuming that two belts at different radii began their evolution at the same time, soon after the debris disc emerged from the gaseous protoplanetary disc. The collision rate in the disc depends strongly on orbital radius, and for an equal number of objects is higher at smaller radii due to both greater relative velocities and a smaller enclosed volume. The brightness of a belt will start to decay when the largest objects start to collide, which will take longer for the outer belt. Therefore, for two belts that have the same initial brightness, the inner one will start to decay first, and the outer belt will follow later, and all other things being equal, in the long term the brightness difference between two belts is set by the difference in their radii.

Wyatt et al. (2007) estimate that the maximum fractional luminosity of an individual belt is

$$f_{\text{max}} = 1.6 \times 10^{-4} r^{3/2} M_*^{-5/6} L_*^{-0.5} t^{-1},$$

where the variables are disc radius (in au), stellar mass and luminosity (in solar units), and system age (in Myr). This fractional luminosity applies to all discs because the brightness decay rate is proportional to the disc mass (and hence the brightness). Thus, all discs tend to the same brightness level once the most massive objects have started to collide. In discs with relatively low initial masses the largest objects take longer to start to collide and decay, and until that time the fractional luminosity lies below the level given by equation (10).

This theory was applied to systems with dust at au scales, such as η Crv and HD 69830 (Wyatt et al. 2007). These discs were found to lie well above $f_{\text{max}}$ and were deemed ‘transient’, in that they could not be described by this model of collisional evolution. Here however, the warm dust components lie roughly in the range of a few to 10 au, so for the typical <Gyr ages of objects in our sample the observed fractional luminosities of both the warm and cool components are comparable with $f_{\text{max}}$, rather than significantly above it. This agreement suggests that the warm components, if interpreted as distinct belts, are undergoing the collisional evolution expected within the framework of this model, but are not brighter than expected (with the notable exception of η Crv). This inference in turn suggests that we may see the differential evolution of warm/cool component brightnesses described above. However, given the radii inferred for the warm components and their correspondingly long collision time-scales, which may be similar to their ages (e.g. Gáspár, Rieke & Balog 2013), the non-detection of such differential evolution would not rule out the two-belt scenario.

To consider the expected evolution of $R_\text{f}$, we assume a typical $R_\text{f}$ of 3, so the radii are a factor of 9 different. Initially, both belts will be very bright, having just emerged from the protoplanetary disc phase, so if both belts are assumed to be near to radiially optically thick then $R_\text{f}$ will be of order unity (but could of course be different, for example if the outer disc is shadowed by the inner one; Kennedy et al. 2014). The brightness of the inner belts is expected to be currently decaying, though this decay may have only begun recently. The outer belts, at roughly 10 times greater distances are not expected to be decreasing in brightness significantly due to much longer collision time-scales (roughly a factor of $10^3$). Therefore, the basic expectation is that the ratio of warm/cool belt brightnesses will start somewhere near unity and decrease over time. Given sufficient time, the difference in belt radii implies this ratio would eventually reach a value

$$R_{\text{f, max}} = \frac{f_{\text{max, warm}}}{f_{\text{max, cool}}} \approx R_\text{f}^{-1/3},$$

or approximately $10^{-2}$ to $10^{-3}$. However, the evolution is sufficiently slow that this limit will not be reached for the <Gyr ages within our sample.

Fig. 16 shows the evolution of $R_\text{f}$ with time for our sample. We use ages from Di Folco et al. (2004), Su et al. (2013), and Chen et al. (2014), but adjust the age of the β Pictoris moving group to 20 Myr (Binks & Jeffries 2014), and the age of HD 61005 to 40 Myr (De Silva et al. 2013). These ages are of course very uncertain and there are many disagreements in the literature, but there is a reasonable age distinction between moving group/association stars and older field stars (listed by Chen et al. 2014), so the ages should at least be representative. No significant evolution is seen, though this lack of evolution does not strongly rule out the hypothesis that the two temperatures correspond to two distinct belts. An additional
Figure 16. Dependence of $R_f$ on stellar age. No trends are visible, but the $\sim 10$ au radii of the warm components and their relatively slow collisional evolution means that the collisional two-belt scenario is not ruled out.

expectation is that the ages of two-temperature systems would be biased towards young ages, because the warm components should decay to undetectable levels more rapidly than the cool components. Our sample is inevitably biased towards younger ages due to young discs being brighter, so any conclusions drawn based on the relative youth of our sample would not be definitive. While Chen et al. (2014) find that two-temperature discs are more likely to be found around younger stars, this tendency is not strong and 50 per cent of their two-temperature discs are $\gtrsim 100$ Myr old.

In summary, we cannot rule out the hypothesis that two-temperature discs arise from two independent belts that are decaying due to collisions. The reason being that the warm belts are at sufficiently large radial distances that their brightness is not at odds with models of collisional evolution.

6.3 Planetary system structure

Our main conclusion is that most two-temperature debris discs comprise two disc components. Consideration of collisional models shows that these components could be two independent belts undergoing normal collisional evolution, analogous to the Solar system’s Asteroid and Edgeworth–Kuiper belts. The exception among our sample is $\eta$ Crv, whose warm component is too bright to be explained by collisional models and may originate from material scattered from the outer belt (e.g. Wyatt et al. 2007; Lisse et al. 2012). In other systems, the inner components may also be linked to the outer belts via inward scattering of material by intervening planets (e.g. Bonsor & Wyatt 2012). While such a scenario is not required to explain the observed warm dust levels, such scattering does not occur in some, and perhaps all, systems.

Considering the scattering scenario, the inner belt is generally thought to originate due to objects depositing their mass near the star after passing inside some comet sublimation and/or disintegration radius (e.g. Kobayashi et al. 2008; Bonsor & Wyatt 2012; Bonsor, Augereau & Thébault 2012). Naively, such a picture is inconsistent with the trend towards higher warm component temperatures for more massive stars, since sublimation should occur at constant temperature. In addition, we find that the warm components can be as cool as 100 K around Sun-like stars, lower than the expected sublimation temperature of $\sim 150$ K. However, as planetesimals are scattered inward they will collide most often at stellocentric distances near the innermost planet where the volume density and relative velocities are highest, and may even be disrupted due to tidal forces given sufficiently close encounters with this planet. In this case, the scattering scenario still allows the creation of two-temperature discs in the absence of thermal destruction of planetesimals within a few au of the star.

Circumstantial evidence that warm and cool belts are separated by planets is provided by extra-solar systems with two disc components and intervening planets, but does not distinguish between the independent-belt and scattering scenarios. The two belts in the HR 8799 system are separated by a series of massive planets (Marois et al. 2008; Reidemeister et al. 2009; Su et al. 2009; Matthews et al. 2014), and HD 95086 has a single planet that resides in a two-temperature disc (Moór et al. 2013; Rameau et al. 2013), though the warm component has yet to be confirmed by high-resolution observations for the latter system.

The $\sim 10$ au typical radii of the warm components of our two-temperature discs do not rule out planets and debris discs at smaller distances. These tend to be much less massive and much harder to detect (e.g. Howard et al. 2012; Kennedy & Wyatt 2013), so it seems probable that low-mass planets and fainter exo-Zodiacal clouds reside interior to the warm components of the discs we have considered here.

Therefore, in either of the above scenarios, two-temperature debris discs seem to give information on the typical scales of outer planetary systems, with the warm/cool temperature ratios suggesting that these typically span a factor of 10 in radius.

7 CONCLUSIONS

We have presented a study of debris discs whose emission spectra are well modelled by dust at two temperatures. These discs are typically assumed to be a sign of multiple belts, so here our goal was to explore whether this emission could arise from dust in a single belt, with the range of temperatures arising from the natural variation in grain temperature with size.

We collected a sample of 48 nearby stars with two-temperature debris discs, and used the ratios of warm/cool component temperatures ($R_f$) and fractional luminosities ($R_T$) as a diagnostic of disc properties. A plot of $R_f$ versus $R_T$ shows that $\eta$ Crv is clearly an outlier among two-temperature discs, having an unusually large warm/cool temperature ratio. We also identified HD 145689 as a potentially interesting system, where the M9 companion may orbit outside or between two debris disc components, or host a disc itself.

Using a grain emission model, we test whether two-temperature discs can arise from single belts. As long as the minimum grain size is set by radiation pressure, two-temperature discs around A-type stars probably arise from multiple belts. In addition, a few two-temperature discs have been confirmed to have multiple belts by high-resolution observations, and these comprise both A-type and Sun-like stars. For Sun-like stars, our single belt model can produce two-temperature discs. Where observations allow tests to be made this model is disfavoured, but it is not conclusively ruled out because not all discs are resolved and/or detected at far-IR/mm wavelengths. In general therefore, the assumption that two-temperature discs have multiple belts should not be made, but it seems likely that the bulk of two-temperature discs do arise from multiple belts. As noted at the outset, PR drag may allow discs whose planetesimals reside in a narrow belt to have two temperatures due to small grains extending in towards the star. Whether this process can generically reproduce a subset of two-temperature discs is clearly worth future effort.
Assuming the multiple belt interpretation is correct, we considered the expected collisional evolution of two distinct belts. Aside from η Crv, the warm components could be independent belts undergoing normal collisional evolution, so it is possible that two-temperature discs represent systems with analogues of the Asteroid and Edgeworth-Kuiper belts that are separated by planets. Scattering of material from the outer regions could still be an important, or even dominant, mechanism for creating two-temperature debris discs, with the warm component comprising material scattered from the cool component, again due to the presence of intervening planets. For either scenario, the ratio of warm/cool component temperatures is indicative of the scale of outer planetary systems, which typically span a factor of about 10 in radius.

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REFERENCES

Acke B. et al., 2012, A&A, 540, A125
Augereau J. C., Lagrange A. M., Mouillet D., Papaloizou J. C. B., Grorod P. A., 1999, A&A, 348, 557
Aumann H. H. et al., 1984, ApJ, 278, L23
Backman D. et al., 2009, ApJ, 690, 1522
Ballering N. P., Rieke G. H., Su K. Y. L., Montiel E., 2013, ApJ, 775, 55
Beichman C. A., Neugebauer G., Habing H. J., Clegg P. E., Chester T.
Beichman C. A. et al., 2006, ApJ, 666, 466
Beichman C. A. et al., 2006, ApJS, 166, 351
Castelli F., Kurucz R. L., 2003, in Piskunov N., Weiss W. W., Gray D. F., Carpenter J. M., Wolf S., Schreyer K., Launhardt R., Henning T., 2005, AJ, 129, 1049
Chen C. H. et al., 2007, ApJ, 666, 466
Chen C. H., Sheehan P., Watson D. M., Manoj P., Najita J. R., 2009, ApJ, 101, 367
Chen C. H., Mittal T., Kuchner M., Forrest W. J., Lisse C. M., Manoj P., Sargent B. A., Watson D. M., 2014, ApJS, 211, 25
Chini R., Kruegel E., Kreysa E., Shustov B., Tutukov A., 1991, A&A, 252, 220
Churchler L., Wyatt M., Smith R., 2011, MNARS, 410, 2
Cutri R. M. et al., 2003, 2MASS All Sky Catalog of Point Sources
De Silva G. M., D’Orazi V., Melo C. A., Torres C. A. O., Gies M., Quast G. R., Sterzik M., 2013, MNARS, 431, 1005
Dent W. R. F. et al., 2014, Science, 343, 1490
Di Folco E., Thévenin F., Kervella P., Domiciano de Souza A., Coudé du Foresto V., Ségransan D., Morel P., 2004, A&A, 426, 601
Dohanyi J. S., 1969, J. Geophys. Res., 74, 2531
Donaldson J. K., Lebreton J., Roberge A., Augereau J.-C., Krivov A. V., 2013, ApJ, 772, 17
Duchêne G. et al., 2014, ApJ, 784, 148
Eiroa C. et al., 2013, A&A, 555, A11
Foreman-Mackey D., Hogg D. W., Lang D., Goodman J., 2013, PASP, 125, 306
Gáspár A., Psaltis D., Rieke G. H., Ozel F., 2012, ApJ, 754, 74
Gáspár A., Rieke G. H., Balog Z., 2013, ApJ, 768, 25
Goodman J., Weare J., 2010, Comm. App. Math. Comp. Sci., 5, 65
Greaves J. S. et al., 2005, ApJ, 619, L187
Helou G., 1989, in Allamandola L. J., Tielens A. G. G. M., eds, Proc. IAU Symp. 153, Interstellar Dust. Kluwer, Dordrecht, p. 285
Holland W. S. et al., 1998, Nature, 392, 788
Holland W. S. et al., 2003, ApJ, 582, 1141
Holmes E. K., Butner H. M., Fajardo-Acosta S. B., Rebull L. M., 2003, AJ, 125, 3334
Houck J. R. et al., 2004, ApJS, 154, 18
Howard A. W. et al., 2012, ApJ, 201, 15
Huélamo N. et al., 2010, A&A, 521, L54
Hughes A. M., Wilner D. J., Andrews S. M., Williams J. P., Su K. Y. L., Murray-Clay R. A., Qi C., 2011, ApJ, 740, 38
Høg E. et al., 2000, A&A, 355, L27
Indriolo N. et al., 2010, A&A, 514, A1
Kalas P., Graham J. R., Clampin M., 2005, Nature, 435, 1067
Kennedy G. M., Wyatt M. C., 2013, MNARS, 433, 2334
Kennedy G. M., Wyatt M. C., Sibthorpe B., Phillips N. M., Matthews B. C., Greaves J. S., 2012, MNARS, 426, 2115
Kennedy G. M. et al., 2014, MNARS, 438, 3299
Kobayashi H., Watanabe S.-I., Kimura H., Yamamoto T., 2008, Icarus, 195, 871
Krist J. E. et al., 2010, AJ, 140, 1051
Laor A., Draine B. T., 1993, ApJ, 402, 441
Lawler S. M. et al., 2009, ApJ, 705, 89
Lebouteiller V., Barry D. J., Spoon H. W. W., Bernard-Salas J., Sloan G. C., Houck J. R., Weedman D. W., 2011, ApJS, 196, 8
Lebreton J. et al., 2012, A&A, 539, A17
Li A., Greenberg J. M., 1997, A&A, 323, 566
Li A., Greenberg J. M., 1998, A&A, 331, 291
Liseau R., Brandeker A., Friedlund M., Olofsson G., Takeuchi T., Artymowicz P., 2003, A&A, 402, 183
Liseau R. et al., 2010, A&A, 518, L132
Lisse C. M. et al., 2012, ApJ, 747, 93
Löhne T. et al., 2012, A&A, 537, A110
Maness H. L., Fitzgerald M. P., Paladini R., Kalas P., Duchene G., Graham J. R., 2008, ApJ, 686, L25
Marois C., Macintosh B., Barman T., Zuckerman B., Song I., Patience J., Lafrenière D., Doyon R., 2008, Science, 322, 1348
Matthews B. C., Kalas P. G., 2007, ApJ, 663, 1103
Matthews B., Kennedy G., Sibthorpe B., Booth M., Brodkoven-Fiene H., Macintosh B., Marois C., 2014, ApJ, 780, 97
Moerchen M. M., Telesco C. M., Packham C., Keheo T. J. J., 2007, ApJ, 655, L109
Moerchen M. M., Telesco C. M., Packham C., 2010, ApJ, 723, 1418
Moór A. et al., 2011, ApJ, 193, 4
Moór A. et al., 2013, ApJ, 775, L51
Morales F. Y. et al., 2009, ApJ, 699, 1067
Morales F. Y., Rieke G. H., Werner M. W., Bryden G., Stapelfeldt K. R., Su K. Y. L., 2011, ApJ, 730, L29
Morales F. Y., Bryden G., Werner M. W., Stapelfeldt K. R., 2013, ApJ, 776, 111
Moshir M. et al., 1990, in IRAS Faint Source Catalogue, version 2.0, 0
Najita J., Absil O., Tamanai A., 2013, A&A, 551, A134
Olofsson J., Henning T., Niebch M., Augereau J.-C., Juhász A., Oliveira I., Absil O., Tamanai A., 2013, A&A, 551, A134

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Table A1. Sample and results of blackbody fitting for 48 two-temperature discs, nine sources marked with an * are part of the DEBRIS sample (Phillips et al. 2010). The ‘Ref’ column notes papers from which far-IR photometry was obtained: 1: IRAS Point Source Catalog (see Beichman et al. 1988), 2: Mosher et al. (1990), 3: Su et al. (2006), 4: Rebull et al. (2008), 5: Carpenter et al. (2008), 6: Bryden et al. (2009), 7: Morales et al. (2009), 8: Su et al. (2009), 9: Sibthorpe et al. (2010), 10: Liseau et al. (2010), 11: Vandebussche et al. (2010), 12: Zuckerman et al. (2011), 13: Moór et al. (2011), 14: Phillips (2011), 15: Acke et al. (2012), 16: Gaspár et al. (2013), and 17: Booth et al. (2013). (Supplementary figures associated with this table are available as supporting information in the online version of this article.)

| Name      | $T_*$ | Age (Myr) | $T_{\text{warm}}$ | $\epsilon_{\text{warm}}$ | $T_{\text{cool}}$ | $\epsilon_{\text{cool}}$ | $\lambda_0$ | $\epsilon_0$ | $\beta$ | $\mathcal{R}_Y$ | $\mathcal{R}_Y$ | $\mathcal{R}_f$ | $\mathcal{R}_f$ | Ref |
|-----------|-------|-----------|-------------------|--------------------------|-------------------|--------------------------|-------------|-------------|--------|----------------|----------------|----------------|----------------|-----|
| HD 377    | 5876  | 170       | 113               | 9                        | 35                | 2                        | 3.2         | 0.3         | 0.20   | 0.03          | 5              |                |                |     |
| HD 6798   | 9120  | 365       | 180               | 16                       | 68                | 5                        | 2.7         | 0.2         | 0.36   | 0.08          | 2              |                |                |     |
| HD 9672   | 8923  | 40        | 143               | 5                        | 52                | 2                        | 61          | 10          | 0.9    | 0.1           | 2.7            | 0.1            | 0.18           | 2   |
| HD 10647* | 6181  | 1560      | 99                | 6                        | 37                | 2                        | 56          | 8           | 1.8    | 0.3           | 2.7            | 0.1            | 0.10           | 0.03| 2, 6, 10, 16 |
| HD 10939  | 9026  | 417       | 200               | 23                       | 59                | 2                        | 3.4         | 0.4         | 0.24   | 0.03          | 1.7            |                |                |     |
| HD 13246  | 6236  | 30        | 231               | 22                       | 72                | 9                        | 3.2         | 0.3         | 3.34   | 0.69          | 12             |                |                |     |
| HD 14055* | 9197  | 300       | 183               | 13                       | 65                | 2                        | 192         | 21          | 1.1    | 0.2           | 2.8            | 0.2            | 0.36           | 0.05| 2, 3, 14     |
| HD 15115  | 6696  | 20        | 163               | 17                       | 55                | 2                        | 2.9         | 0.3         | 0.11   | 0.02          | 2.13           |                |                |     |
| HD 15745  | 6924  | 20        | 104               | 6                        | 46                | 3                        | 2.3         | 0.1         | 1.33   | 0.20          | 2.13           |                |                |     |
| HD 16743  | 7018  | 200       | 127               | 9                        | 48                | 3                        | 2.6         | 0.2         | 0.18   | 0.04          | 1.3            |                |                |     |
| HD 22049* | 5100  | 850       | 119               | 7                        | 31                | 1                        | 73          | 11          | 1.1    | 0.1           | 3.8            | 0.2            | 0.64           | 0.11| 2.6          |
| HD 23267  | 9992  | 60        | 330               | 42                       | 138               | 11                        | 2.4         | 0.3         | 0.98   | 0.32          | 7              |                |                |     |
| HD 25457  | 6303  | 70        | 138               | 13                       | 54                | 5                        | 2.5         | 0.2         | 0.56   | 0.13          | 2.5            |                |                |     |
| HD 30447  | 6794  | 30        | 133               | 11                       | 58                | 2                        | 2.3         | 0.2         | 0.13   | 0.03          | 2.13           |                |                |     |
| HD 31295  | 8673  | 123       | 168               | 17                       | 58                | 3                        | 2.9         | 0.3         | 0.32   | 0.05          | 2.3, 3, 14     |                |                |     |
| HD 32297  | 7654  | 11        | 203               | 9                        | 80                | 2                        | 237         | 105         | 0.5    | 0.2           | 2.5            | 0.1            | 0.16           | 0.01| 1          |
| HD 38056  | 9900  | 293       | 302               | 36                       | 88                | 4                        | 3.5         | 0.4         | 0.78   | 0.13          | 7              |                |                |     |
| HD 38206  | 9825  | 30        | 233               | 8                        | 68                | 2                        | 3.5         | 0.1         | 0.68   | 0.04          | 2.7            |                |                |     |
| HD 38207  | 6795  | 534       | 123               | 7                        | 52                | 2                        | 2.4         | 0.1         | 0.14   | 0.03          | 5              |                |                |     |
| HD 39060* | 8090  | 20        | 493               | 19                       | 108               | 1                        | 204         | 15          | 0.9    | 0.1           | 4.6            | 0.2            | 0.57           | 0.03| 2, 11, 14 |
| HD 61005  | 5492  | 40        | 123               | 8                        | 54                | 1                        | 2.3         | 0.1         | 0.07   | 0.01          | 1.5            |                |                |     |
| HD 70313  | 8466  | 200       | 183               | 19                       | 62                | 3                        | 3.0         | 0.3         | 0.33   | 0.05          | 2.7            |                |                |     |
Table A1 – continued

| Name            | $T_\star$ (K) | Age (Myr) | $T_{warm}$ | $\epsilon_{T_{warm}}$ | $T_{cool}$ | $\epsilon_{T_{cool}}$ | $\lambda_0$ | $\epsilon_{\lambda_0}$ | $\beta$ | $\epsilon$ | $R_T$ | $\epsilon_R_T$ | $R_f$ | $\epsilon_R_f$ | Ref          |
|-----------------|---------------|-----------|------------|-----------------------|------------|-----------------------|-------------|------------------------|--------|------------|--------|----------------|------|----------------|--------------|
| HD 71722        | 8917          | 324       | 250        | 30                     | 75         | 2                     | 3.4         | 0.4                    | 0.29   | 0.05       | 7      |                |      |                |              |
| HD 79108        | 9350          | 283       | 230        | 23                     | 69         | 5                     | 3.3         | 0.3                    | 0.73   | 0.11       | 2, 7   |                |      |                |              |
| HD 80950        | 9684          | 138       | 294        | 21                     | 137        | 7                     | 2.1         | 0.1                    | 1.02   | 0.24       | 7      |                |      |                |              |
| HD 98673        | 7958          | 737       | 244        | 36                     | 82         | 7                     | 3.0         | 0.4                    | 1.05   | 0.28       | 7      |                |      |                |              |
| HD 107146       | 5893          | 100       | 103        | 4                      | 45         | 1                     | 338         | 20                     | 0.8    | 0.0        | 2.3    | 0.1           | 0.1   | 0.01          | 2, 5         |
| HD 109085*      | 6934          | 1380      | 254        | 20                     | 39         | 2                     | 34          | 12                     | 0.3    | 0.1        | 6.5    | 0.5           | 7.7   | 1.36          | 2            |
| HD 110411*      | 8920          | 86        | 253        | 32                     | 79         | 2                     | 75          | 9                      | 0.6    | 0.2        | 3.2    | 0.4           | 0.32  | 0.08          | 2, 14, 17    |
| HD 1352162*     | 8646          | 315       | 253        | 8                      | 42         | 4                     | 93          | 24                     | 1.6    | 0.4        | 2.5    | 0.2           | 1.55  | 0.1           | 2, 14         |
| HD 136246       | 8519          | 16        | 211        | 29                     | 52         | 6                     | 4.0         | 0.6                    | 0.43   | 0.09       | 7      |                |      |                |              |

Table A2. Sub-mm and mm photometry of targets in our sample. The $3\sigma$ limit column indicates that the flux is an upper limit. Fluxes without this flag are not necessarily significant detections.

| Name            | $\lambda$ ($\mu$m) | Instrument | Flux (mJy) | Unc (mJy) | $3\sigma$ flag | References         |
|-----------------|---------------------|------------|------------|------------|----------------|--------------------|
| HD 377          | 3000                | OVRO      | 0.79       | 0.61       |                | Carpenter et al. (2005) |
| HD 377          | 1200                | IRAM      | 4          | 1          |                | Roccatagliata et al. (2009) |
| HD 377          | 2700                | OVRO      | 0.32       | 0.8        |                | Carpenter et al. (2005) |
| HD 9672         | 1300                | IRAM      | 13.9       | 2.48       |                | Walker & Butner (1995) |
| HD 14055        | 850                 | SCUBA     | 5.5        | 1.8        |                | Williams & Andrews (2006) |
| HD 15115        | 850                 | SCUBA     | 4.9        | 1.6        |                | Williams & Andrews (2006) |
| HD 216956*      | 8560                | SCUBA     | 225        | 10         |                | Shuret et al. (2014)  |
| HD 22049        | 1200                | IRAM      | 12.7       | 3.9        |                | Walker & Butner (1995) |
| HD 22049        | 1300                | MPIR      | 24.2       | 3.4        |                | Chini et al. (2001)  |
| HD 22049        | 450                 | SCUBA     | 225        | 10         |                | Greaves et al. (2005) |
| HD 22049        | 850                 | SCUBA     | 37         | 3          |                | Greaves et al. (2005) |
| HD 22049        | 450                 | SCUBA     | 250        | 20         |                | Backman et al. (2009) |
| HD 22049        | 350                 | CSO       | 366        | 50         |                | Shuret et al. (2014)  |
| HD 22049        | 850                 | SCUBA     | 40         | 1.5        |                | Carpenter et al. (2005) |
| HD 25457        | 1200                | SEXT      | -8         | 14         |                | Carpenter et al. (2005) |
| HD 25457        | 870                 | LABOCA    | 9.9        |            | 1               | Nilsson et al. (2010)  |
| HD 25457        | 2700                | OVRO      | -1.51      | 1.33       |                | Carpenter et al. (2005) |
| HD 25457        | 3000                | OVRO      | 0.37       | 0.62       |                | Carpenter et al. (2005) |
| HD 30447        | 870                 | LABOCA    | 6.9        | 5          |                | Nilsson et al. (2010)  |
| HD 32297        | 870                 | LABOCA    | 19.5       |            |                | Nilsson et al. (2010)  |
| HD 32297        | 1300                | CARMA     | 5.1        | 1.1        |                | Maness et al. (2008)  |
| HD 38207        | 1200                | SEXT      | -3         | 12         |                | Carpenter et al. (2005) |
| HD 38207        | 1200                | IRAM      | 0.33       |            |                | Roccatagliata et al. (2009) |
| HD 39060        | 1200                | SIMBA     | 24.3       | 3          |                | Liseau et al. (2003)  |
| HD 39060        | 870                 | LABOCA    | 63.6       | 6.7        |                | Nilsson et al. (2009)  |
| HD 39060        | 850                 | SCUBA     | 58.3       | 6.5        |                | Holland et al. (1998) |
| HD 39060        | 1300                | MPIR      | 24.9       | 2.6        |                | Chini et al. (1991)  |
| HD 61005        | 870                 | LABOCA    | 18         |            | 1               | Nilsson et al. (2010)  |
| Name          | λ(µm) | Instrument | Flux (mJy) | Unc (mJy) | 3σ flag | References              |
|--------------|-------|------------|------------|-----------|---------|-------------------------|
| HD 61005     | 1200  | SEST       | 31         | 34        |         | Carpenter et al. (2005) |
| HD 61005     | 350   | CSO        | 95         | 12        |         | Roccatagliata et al. (2009) |
| HD 107146    | 350   | CSO        | 319        | 6         |         | Roccatagliata et al. (2009) |
| HD 107146    | 3000  | OVRO       | 1.42       | 0.23      |         | Carpenter et al. (2005) |
| HD 107146    | 850   | SCUBA      | 20         | 3.2       |         | Najita & Williams (2005) |
| HD 107146    | 880   | SMA        | 36         | 1         |         | Hughes et al. (2011)    |
| HD 107146    | 450   | SCUBA      | 130        | 40        |         | Williams et al. (2004)  |
| HD 107146    | 450   | SCUBA      | 130        | 12        |         | Najita & Williams (2005) |
| HD 107146    | 850   | SCUBA      | 20         | 4         |         | Williams et al. (2004)  |
| HD 109085    | 450   | SCUBA      | 58.2       | 9.8       |         | Wyatt et al. (2005)     |
| HD 109085    | 850   | SCUBA      | 15.5       | 1.4       |         | Duchêne et al. (2014)   |
| HD 109085    | 850   | SCUBA      | 14.3       | 1.8       |         | Wyatt et al. (2005)     |
| HD 109085    | 850   | SCUBA      | 12.8       | 5.2       |         | Nilsson et al. (2010)   |
| HD 172167    | 850   | SCUBA      | 45.7       | 5.4       |         | Holland et al. (1998)   |
| HD 172167    | 1300  | IRAM       | 11.4       | 1.7       |         | Wilner et al. (2002)    |
| HD 172167    | 3300  | IRAM       | 0.39       |           | 1       | Wilner et al. (2002)    |
| HD 181296    | 870   | LABOCA     | 14.4       |           | 1       | Nilsson et al. (2009)   |
| HD 181327    | 870   | LABOCA     | 51.7       | 6.2       |         | Nilsson et al. (2009)   |
| HD 181327    | 3190  | ATCA       | 0.72       | 0.25      |         | Lebreton et al. (2012)  |
| HD 192425    | 1300  | SMTO       | 7.95       |           | 1       | Holmes et al. (2003)    |
| HD 192425    | 870   | SMTO       | 33.3       |           | 1       | Holmes et al. (2003)    |
| HD 216956    | 450   | SCUBA      | 595        | 35        |         | Holland et al. (2003)   |
| HD 216956    | 1300  | MPIfR      | 21         | 2.5       |         | Chini et al. (1991)     |
| HD 216956    | 850   | SCUBA      | 81         | 7.2       |         | Holland et al. (1998)   |
| HD 218396    | 850   | SCUBA      | 10.3       | 1.8       |         | Holland et al. (2003)   |
| HD 218396    | 1100  | UKT14      | 33         |           | 1       | Williams & Andrews (2006) |

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figures. Supplementary figures associated with Table A1. (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu1665/-/DC1).

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