The transition disc frequency in M stars

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ABSTRACT

We re-examine the recent suggestion of a high fraction of transition discs (i.e. those with a cleared inner hole) in M stars, motivated by the fact that we expect that, for M stars, even discs without inner holes should exhibit very weak excess shortward of around 10 µm. Our analysis of spectral energy distribution models suggest that this indeed means that M stars where a detectable excess begins at around 6 µm may be mis-classified as transition discs when in fact they have optically thick dust extending in to the dust sublimation radius. Consequently, we estimate that the transition disc fraction among M stars in the Coronet cluster is ∼ 15 ± 10% (rather than the recently claimed value of 50%). This revised figure would imply that the transition disc fraction is not after all markedly higher in later type stars. We suggest that for M stars, transition discs can only be readily identified if they have emission that is close to photospheric out to > 10 µm.

Key words: accretion, accretion discs:circumstellar matter- planetary systems:protoplanetary discs - stars:pre-main sequence

1 INTRODUCTION

There is currently considerable interest in so-called ‘transition discs’ around young stars, that is systems whose spectral energy distribution (SED) suggests that their inner regions are devoid of dust (e.g. Calvet et al 2002, D’Alessio et al 2005, Forrest et al 2004). As the nomenclature suggests, these objects are deemed to be in a state of transition between disc-possessing and discless status and are of interest inasmuch as their properties may shed light on the processes that disperse discs around young stars. Understanding disc dispersal is evidently of relevance to planet formation, whether or not, as is currently debated, the dispersal interrupts the process or whether it is instead a signature of planet building.

Transition discs are generally identified as objects whose SED indicates the presence of optically thick dust at large radius (i.e. excess emission at mid infrared wavelengths or beyond) but which do not show evidence of excess emission at shorter infrared wavelengths. This is most readily interpreted as resulting from an inner hole in the disc, and transition objects have been modeled in detail under this assumption (e.g. Rice et al 2003, Quillen et al 2004, Rice et al 2006). A property of transition discs, which has been noted since the earliest studies (e.g. Hartigan et al 1990, Kenyon and Hartmann 1995) is that they appear to be rather rare, typically being outnumbered by about a factor ten by objects whose discs lack inner holes (Duvert et al 2000, Andrews and Williams 2005, Hartmann et al 2005). A natural inference from this observation is that the timescale for disc clearing is relatively short, so that rather few objects are caught in the act of transition. A number of models have been motivated by this apparent observational requirement of two timescales - i.e. an overall disc lifetime and a substantially shorter final clearing timescale (Clarke et al 2001, Alexander et al 2006).

Now that a larger sample of transition objects have been identified, thanks to the acquisition of broad band SEDs out to mid infrared wavelengths using Spitzer, this conclusion appears in general to have been upheld, with 10% still representing a rough value for the fraction of young stars in transition (Sicilia-Aguilar et al 2006, Padgett et al 2006, Lada et al 2006, Hernandez et al 2007). This consensus was however notably challenged by the recent study of discs in the Coronet cluster by Sicilia-Aguilar et al 2008 (hereafter SA08) which claimed a transition disc fraction of around 50%. The authors drew attention to the preponderance of M stars in their sample and suggested accordingly that a lengthy transition phase may be a feature of later type stars or that some of these discs could have been formed already as flattened or transition-like structures.

If substantiated, such a claim would have important implications for disc clearing: in particular a lengthy transition phase would suggest that models that have been developed for G and K type stars, involving rapid clearing, are only applicable in hotter stars, a fact that could in itself lend clues about the dispersal process. However, before exploring such theoretical implications it is necessary to be clear that one is indeed seeing evidence for an extended transition phase in M stars. In this Letter, we argue that the classification of a large fraction of such stars as transition objects is a consequence of the fact that, in the case of cooler stars, one has to go to longer wavelengths before one can unambiguously disentangle disc emission from that of the stellar photosphere. Thus the SEDs seen in many M stars that have been dubbed as transition objects (i.e. with excess emission becoming apparent only beyond 6 µm) is actually what is to be expected in the case of discs extend-
ing all the way in to the dust sublimation radius; such discs obviously do produce emission at less than 6 \mu m, but this is difficult to separate from that of the stellar photosphere.

In Section 2, we set out simple arguments why the wavelength at which one attains a given ratio of disc to stellar emission scales, in the case of an untruncated disc, with the reciprocal of the stellar temperature. In Section 3 we illustrate these ideas with some specimen SEDs computed using the model database and model fitting tool of Robitaille et al (2006, 2007). Section 4 summarises our conclusions.

2 SIMPLE ARGUMENTS

We consider the case of an optically thick disc that is heated entirely by reprocessing of stellar radiation. We assume the star radiates as a black body with temperature \( T_* \), and the disc radiates as a sequence of black bodies of various temperatures, \( T(r) \). Radiative equilibrium relates \( T(r) \) to \( T_* \) via a relation which, for the purpose of the simple argument presented here, we paramaterise to be of the form

\[
T(r) \sim T_* (r/r_\ast)^{-q}
\]

where the value of \( q \) is dictated by the geometry of the disc surface, e.g. \( q = 0.75 \) for a flat reprocessing disc and \( q \rightarrow 0.5 \) in the case of a quasi-spherical distribution: observationally, the slope of the broadband SEDs in T Tauri stars suggests \( q \sim 0.5 \), which requires the disc to be significantly flared (Kenyon and Hartmann 1987). The ratio of the fluxes emitted by the disc to that emitted by the star at wavelength \( \lambda \) is thus given by the ratio of the product of black body fluxes and emitting areas for the star and disc. As a single temperature black body, the star’s emitting area is evidently \( \propto r_*^2 \). The effective emitting area of the disc at wavelength \( \lambda \) is \( \propto r_\ast^2 \), where \( r_\ast \) is the radius in the disc with temperature \( (T_\ast) \) for which the black body emissivity peaks at wavelength \( \sim \lambda \). We thus have

\[
\frac{L_\ast(\lambda)}{L(\lambda)} = \frac{B_\lambda(T_\ast)}{B_\lambda(T_\ast)} \left( \frac{r_\ast}{r_\ast} \right)^2
\]

(2)

where \( B_\lambda(T) \) is the usual black body (Planck) emissivity. Substituting the functional form of \( B_\lambda(T) \) and applying the parameterisation of \( r_\ast/r_* \) from (1) above, we then obtain

\[
\frac{L_\ast(\lambda)}{L(\lambda)} = \frac{\exp(\frac{hc}{\lambda kT_\ast}) - 1}{\exp(\frac{hc}{\lambda kT_*}) - 1} \left( \frac{T_\ast}{T_*} \right)^{2/q}
\]

(3)

We have however defined \( T_\ast \) such that the expression containing the exponential on the denominator is of order unity (i.e. we select the region of the disc whose temperature means that its black body curve is peaked at \( \sim \lambda \)). Therefore, since this also implies that \( T_\ast \propto 1/\lambda \) we can write that the disc to star flux ratio scales with \( \lambda \) and \( T_* \), according to

\[
\frac{L_\ast(\lambda)}{L(\lambda)} \propto \exp\left(\frac{hc}{\lambda kT_*}\right) - 1 \left( \frac{AT_*}{T_*} \right)^{2/q}
\]

(4)

We thus see immediately that this ratio is a function of the product \( AT_* \) and thus that the wavelength at which a given contrast between the disc and the star is achieved is inversely proportional to the stellar temperature. Furthermore, provided the star’s spectrum is in the Rayleigh Jeans tail at wavelength \( \lambda \), the scaling simplifies to

\[
\frac{L_\ast(\lambda)}{L(\lambda)} \propto (AT_*)^{2/q-1}
\]

(5)

For \( q = 0.5 \), the ratio thus scales with \( T_*^2 \). Thus the disc to star ratio at fixed wavelength for a pure reprocessing disc is larger for hotter stars. This result can be understood since, although hotter stars are brighter at any given wavelength, this is more than offset by the fact that the region of the disc contributing emission at this wavelength is larger in the case of hotter stars.

The above simple argument implies that in the case of discs that extend inwards to a fixed inner temperature (e.g. untruncated discs which are optically thick as far in as the dust sublimation radius), it is harder to detect disc signatures, at a given wavelength, in the case of a cooler star. By the same token, if the disc is truncated so as to remove disc emission at a given wavelength, it is harder to detect the absence of disc emission at this wavelength. Thus it may be hard to distinguish truncated discs and untruncated discs if the wavelength of observation is too low. For example, if in the case of G stars one starts to detect the presence (or absence) of excess disc emission at a few microns, then - with given measurement errors - it becomes possible to do the same for M stars at a wavelength that is greater than this by the ratio of the stellar temperatures (i.e. a factor \( \sim 1.5 \)).

These general arguments are borne out by the SED models of Robitaille et al (2006) shown in Figure 1 where we have selected models for a class II G star (red) and a class II M star (black). The IDs of the models are 3013671 and 3009553 respectively. These models have disc accretion rates of \( \sim 5 \times 10^{-10} \ M_\odot / \text{yr} \); at such accretion rates the discs are in both cases optically thick as far in as the dust sublimation radius, but in neither case is the accretion luminosity signif-

Figure 1. Top panel: Model SEDs for a class II G star (red) and a class II M star (black) from the set of Robitaille et al (2006). The model parameters are summarised in columns 2 and 3 of Table 1. The solid lines represent the total normalised fluxes, the dashed lines represent the normalised photospheric fluxes and the dash-dot lines represent the thermal emission. Bottom panel: Ratio of total to photospheric flux for the M star (black solid line) and G star (red solid line) models. A ratio of 1 is shown by the horizontal dotted line. The blue dash-dot line shows the total to photospheric flux ratio for the G star model divided by that of the M star model. The vertical dotted line in both panels is given to guide the eye and it marks the 6 \mu m location.

\[ \frac{L_\ast(\lambda)}{L(\lambda)} \propto (AT_*)^{2/q-1} \]

(5)

The exact parameter values for these models are available at [http://www.astro.wisc.edu/protostars](http://www.astro.wisc.edu/protostars).
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3 COMPARISON OF MODELS WITH DATA

Here we focus on the issue of whether the objects classified by SA08 as M star transition discs are genuinely undergoing a phase of inner disc clearing. In Figures 2 and 3 we reproduce the SEDs of the claimed M star transition discs, which were selected on the grounds that the emission was apparently photospheric out to 6 μm but rose at longer wavelengths.

We have used the model database and fitting tool of Robitaille et al. (2006, 2007) in order to analyse the SEDs of those objects in the Coronet cluster that were classified as transition objects (TO) by SA08. The observational data were obtained by digitally sampling the SEDs shown in Figures 7 and 8 of SA08. The fitting tool was then used to find all models which provide a good fit to these observations, characterising each fit by a $\chi^2$ value. In the case of five of the sources, a spectral type is available (SA08). For these sources, we reject models which differ by more than one spectral subclass. For example, for CrA-466, classified as M2, we reject all models later than M3 and earlier than M1. The range of parameters of the models providing a good fit (which we define as $\chi^2 - \chi^2_{\text{best}} < 2n_{\text{data}}$, where $\chi^2_{\text{best}}$ is the $\chi^2$ of the best fitting model and $n_{\text{data}}$ is the number of data points) are in each case given in Table 1; in Figures 2 and 3 the solid black line represents the SED of the best-fit model, the dashed black line represents the spectrum of the central source, and the solid black lines show other models providing a good fit according to the above criterion.

From our SED fitting, we found that only two of the seven claimed TO’s cannot be fit by models with discs extending all the way to the dust sublimation radius, and hence show evidence of

Figure 2. Left Panels: Model fits to the digitised data points of TOs from the SA08 sample which were confirmed as bona-fide TOs by our SED fitting. The solid and dashed black lines show the best fitting model and corresponding stellar photosphere model, while the solid grey lines show other models providing a good fit. Right Panels: The hashed histograms represent the distribution of derived values of the inner hole radius in units of the dust sublimation radius for the models which fit the SED of each object. The grey histogram shows the distribution of this quantity for all the models in the Robitaille et al. (2006) set. Both histograms are normalised so that their peak value is 1.

Figure 3. Left Panels: Model fits to the digitised data points of the TOs from the SA08 sample which can be well fit by untruncated models. The lines and histograms are as in Figure 2.
a cleared inner hole. Figure 2 (left panels) shows the model fits ($\chi^2 - \chi^2_{best} < 2n_{data}$) to the digitized data points of the bona-fide TOs confirmed by SED fitting. The right-hand panels (hashed histogram) depict the distribution of derived values of the inner hole radius in units of the dust sublimation radius, for the subset of models that provide a good fit to the SED of each object; this is compared (grey histogram) with the distribution of this quantity for all the 2 x 10^5 models in the grid. Figure 3 shows SED fits and disc inner radius distributions for the objects that had been previously classified as TOs by SA08, but turned out to be well-fit by untruncated disc models. We also note that our fit for CrA-205 shown in Figure 3 does not go through the 8 $\mu$m IRAC point. SA08, however, report an error of 0.38 magnitudes on the 8 $\mu$m IRAC point and an uncertain measurement for the 24 $\mu$m MIPS point: furthermore the IRS spectra published for this object in the 8 $\mu$m region has a very low signal-to-noise.

On this basis, we estimate that the true fraction of M stars in the Coronet that are demonstrably in transition (i.e. have discs where there is good evidence for truncation at a radius exceeding the dust sublimation radius) is closer to ~ 2/13 = 15% (with an uncertainty of $\sqrt{13} = 10\%$ due to small number statistics).

Finally, we note that the models that fit the observations all require that the dust distribution is at most modestly flared and that the dust is apparently settled relative to the gas distribution. This is shown in the last two columns of Table 1, which list the range of values of the scaleheight of the disc at 100 AU divided by the scaleheight the disc would have if it was in hydrostatic equilibrium with $T \propto r^{-1.5}$ (which would imply $h \propto r^{0.4}$, D’Alessio et al. 1997, Chiang & Goldreich 1997). Such a tendency towards flatter discs (i.e. with a more settled dust component) in lower mass stars has been noted by a number of previous authors (Pascucci et al 2003, Apai et al 2004, Allers et al 2006).

4 CONCLUSIONS
We have shown that in the case of pure reprocessing discs, the contribution from the disc is small in M stars, shortward of 6 $\mu$m, even if the disc extends all the way in to the dust sublimation radius. We can understand this based on the simple arguments presented in Section 2: although the photospheric output is lower in cooler stars, this is more than offset by the fact that the area of disc emitting at a given wavelength is lower, and in consequence the contrast between the thermal and stellar contribution (disc to star ratio) at given wavelength is lower than in the case of a hotter star. This means that reprocessing discs around M stars will tend to have the sorts of SEDs typified by Cr-466 (see Figure 3), being close to photospheric at < 6 $\mu$m, but evidencing excess emission at longer wavelength. Such discs are therefore not necessarily in transition. Spectral models (Figure 2) suggest that one only starts to get unambiguous evidence of holes in M star discs in cases where the SED is close to photospheric out to > 10 $\mu$m. Thus an object like CrA-4109 is likely to contain an inner hole. Based on these arguments we suggest that the transition disc frequency for M stars in the Coronet has been over-estimated and that, as a preliminary estimate, 15 ± 10% might be a closer figure.

The high-temperature analogue of this effect was discussed by Whitney et al. (2004), who found that the infrared excess from the disc appears enhanced compared to cooler stars, resulting in a misidentification of hotter sources as younger (Class I) sources. As shown by their models, a range of stellar temperatures all result in the same shape for their thermal spectrum, and, as we discussed earlier, the difference in the apparent excess is due to the contrast between the stellar and thermal emission. Whitney et al. (2004) describe the behavior as a separation in the wavelengths of the peak emission between the stellar and thermal emission, which is much larger in hotter stars, resulting in the thermal emission being much more evident in the 1-10 $\mu$m range.

Another effect that should perhaps be mentioned here is that M star luminosities are generally lower than G star luminosities, hence their dust sublimation radius is on average smaller. In some cases one might expect that the dust sublimation radius may reside inside the magnetic truncation radius, as predicted by magnetic accretion models. In such cases one might also detect an infrared hole, even though the object is not a transition disc. This effects does indeed hint at the possibility that M star clusters may exhibit a larger apparent TO ratio. Our analysis of the Coronet cluster, however, implies a TO fraction of 15 ± 10%, only marginally larger than those observed for G stars.

Finally, we note that our discussion appears to imply that inner holes are harder to detect in M stars than in G stars. This conclusion however needs to be qualified, since this refers to the detectability of truncation according to the presence or absence of excess at a given wavelength. We noted in Section 2 that the wavelength at which the disc to star ratio equals a given value is inversely proportional to temperature, and therefore one can test for truncation in lower mass stars by going to longer wavelengths. In brief, if one’s measurement errors allow one to detect a given ratio of disc to photospheric emission, then it allows one to detect holes which deplete dust that is hotter than a fixed fraction of the stellar temperature. Given the form of the disc temperature profile (equation 1) this minimum detectable hole then corresponds to a fixed multiple of the stellar radius. Therefore, if one has observations extending to long enough wavelength, one can detect physically smaller holes in (physically smaller) cooler stars. We suggest, on inspection of the models shown in Section 3, that in M stars one can safely label a disc as ‘transitional’ only if the upturn in flux occurs at wavelengths longer than 10 $\mu$m, but emphasise that more detailed modeling is required to make this figure precise.

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Table 1. Parameters of the models presented in Figures 2 and 3.

| Source name | \( M_{\text{disc}} \) (\( M_\odot \)) | \( \dot{M}_{\text{disc}} \) (\( M_\odot /\text{yr} \)) | \( R_{\text{min}} \) (\( R_{\text{sub}} \)) | \( h \) at 100 AU (AU) | \( h/h_{\text{SEQ}} \) at 100 AU |
|-------------|---------------------------------|---------------------------------|-----------------|-----------------|-----------------|
| CrA-205     | 2.7 \times 10^{-8} - 3.8 \times 10^{-4} | 8.5 \times 10^{-14} - 2.7 \times 10^{-10} | 1.0 - 1.2 | 1.0 - 1.2 | 0.2 - 0.5 |
| CrA-466     | 3.3 \times 10^{-4} - 9.5 \times 10^{-3} | 4.5 \times 10^{-10} - 2.3 \times 10^{-8} | 1.0 - 2.2 | 2.0 - 8.0 | 0.3 - 0.7 |
| CrA-4109    | 6.8 \times 10^{-7} - 2.1 \times 10^{-3} | 5.5 \times 10^{-13} - 2.0 \times 10^{-11} | 232.5 - 596.3 | 2.3 - 4.3 | 0.3 - 0.5 |
| CrA-4111    | 2.2 \times 10^{-6} - 1.7 \times 10^{-4} | 2.1 \times 10^{-11} - 4.0 \times 10^{-10} | 200.3 - 220.9 | 2.6 - 3.1 | 0.3 - 0.3 |
| G-14        | 3.5 \times 10^{-7} - 7.8 \times 10^{-4} | 2.2 \times 10^{-13} - 1.8 \times 10^{-10} | 1.0 - 1.1 | 3.9 - 7.5 | 0.4 - 0.6 |
| G-65        | 1.6 \times 10^{-6} - 1.5 \times 10^{-2} | 3.9 \times 10^{-13} - 1.7 \times 10^{-8} | 1.0 - 5.5 | 1.5 - 7.5 | 0.3 - 0.7 |
| G-87        | 1.6 \times 10^{-6} - 4.0 \times 10^{-3} | 3.8 \times 10^{-13} - 5.2 \times 10^{-9} | 1.0 - 1.9 | 1.6 - 8.7 | 0.3 - 0.6 |

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