

WISE circumstellar discs in the young Sco-Cen association

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ABSTRACT

We present an analysis of the *WISE* photometric data for 829 stars in the Sco-Cen OB2 association, using the latest high-mass membership probabilities. We detect infrared excesses associated with 135 BAF-type stars, 99 of which are secure Sco-Cen members. There is a clear increase in excess fraction with membership probability, which can be fitted linearly. We infer that 41 ± 5 per cent of Sco-Cen OB2 BAF stars have excesses, while the field star excess fraction is consistent with zero. This is the first time that the probability of non-membership has been used in the calculation of excess fractions for young stars. We do not observe any significant change in excess fraction between the three subgroups. Within our sample, we have observed that B-type association members have a significantly smaller excess fraction than A- and F-type association members.

Key words: planets and satellites: formation – protoplanetary discs – circumstellar matter – stars: early-type – open clusters and associations: individual: Sco-Cen, Sco OB2.

1 INTRODUCTION

Many young (~ 1 – 10 Myr) stars of all types, ranging from tens of solar masses down to the smallest brown dwarves and in all environments, are surrounded by circumstellar discs (Strom et al. 1989; Lada et al. 2000; Carpenter et al. 2006). A variety of observations have provided us with an overall timeline of disc evolution. The inner portion of the disc (≤ 1 au) dissipates by the age of 10 Myr in all but a small fraction of stars (Mamajek et al. 2004; Silverstone et al. 2006). From the age of 10 Myr onwards, there is an observed decline in the $24 \mu\text{m}$ excess relative to the photosphere for stars of B to K type (Rieke et al. 2005; Gáspár et al. 2009). It has been postulated that planetesimal stirring through stellar ages of 5–20 Myr could produce an increase in the strength of the $\sim 24 \mu\text{m}$ excess with age (Kenyon & Bromley 2008); however, the current data do not show a statistically significant increase (Carpenter et al. 2009).

The Sco-Cen association and its three subgroups – Upper Scorpius (US), Upper Centaurus Lupus (UCL) and Lower Centaurus Crux (LCC) – provide three important constant-age samples within which to study circumstellar discs around young stars. The subgroups have ages of ~ 5 , ~ 16 and ~ 17 Myr, respectively, and are located less than 150 pc from the Sun (de Zeeuw et al. 1999). Previous studies (Carpenter et al. 2006, 2009) have investigated IRAC, IRS and *Spitzer* photometric data ranging from 4.5 to $70 \mu\text{m}$ in the US subgroup. They identified 54 stars with $24 \mu\text{m}$ excesses in their sample of 205 targets and found that discs around BAF-type stars appear to be comprised of dusty debris, while discs associated with

K- and M-type stars are likely optically thick primordial discs which are remnants of the star formation process. The older Sco-Cen subgroups, UCL and LCC, have received considerably less attention; only a handful of studies have observed small numbers of UCL and LCC stars (Su et al. 2006; Carpenter et al. 2009). The recent study by Chen et al. (2011) reports the detection of 41 new discs around F- and G-type Sco-Cen stars.

New Bayesian membership probabilities for the high-mass members (B to F type) of the Sco-Cen association are now available (Rizzuto, Ireland & Robertson 2011), and preliminary photometric data from the *WISE* mission have been released (Wright et al. 2010). In this Letter, we present an analysis of the *WISE* photometry for Sco-Cen members to search for circumstellar discs in three constant-age samples.

2 DATA SAMPLE

In this study, we take our sample from the *Hipparcos* Sco-Cen membership study of Rizzuto et al. (2011). All stars with membership probabilities of 5 per cent and greater were cross-referenced with the *WISE* preliminary data release. This resulted in a sample of 829 stars with spectral types ranging from early B to late F ($B - V \leq 0.6$), brighter than 9th visual magnitude and within the area of sky bounded by ($285 \leq l \leq 360$) and ($-10 \leq b \leq 60$). Taking into consideration membership probabilities, this equates to ~ 400 true members. Membership as described in Rizzuto et al. (2011) is based purely on kinematic and positional properties of the targets, and hence the selection is believed to be unbiased with regard to the presence of circumstellar discs. We have chosen to include the low membership probability stars in this study in order to use a potential

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relationship between excess fraction and probability of membership to infer a more accurate excess fraction for secure members.

3 WISE EXCESSES

The *WISE* mission data provide photometry in four bands, W_1 , W_2 , W_3 and W_4 , with central wavelengths of 3, 4.5, 12 and 22 μm , respectively (Wright et al. 2010). In this study, we present an analysis of three *WISE* colours: $W_1 - W_2$, $W_1 - W_3$ and $W_1 - W_4$. Inspection of the *WISE* photometry for band W_2 shows a clear bias at the bluest end of our membership sample towards poorly fitted point spread functions, resulting in untrustworthy W_2 photometry. For this reason, the long wavelength colours were constructed with W_1 , which shows a uniform distribution across spectral type of poor photometry fits. Analysis of these three colours will provide three different classes of detected excesses: (1) excesses in all colours, (2) excesses in only the short wavelength filters and (3) excess in only the longer or longest wavelengths. It is expected that a disc-produced excess detected at bluer colours will also be detected at longer colours; hence, excesses in only the blue colours will indicate contaminated photometry.

Stellar photospheric emission is expected to vary linearly with 2MASS ($J - K_s$) colour. To determine the photospheric colours, we have applied an iterative fitting procedure. Objects which were clear outliers in the particular *WISE* colour were first removed and then the software package MPFIT was used to fit a line to the sample. Objects separated from the fitted line by more than twice the dispersion of the residuals were then removed as outliers. The process was then repeated until no further objects were removed. This fitting procedure was carried out using only the stars with greater than 60 per cent membership probability in order to ensure that the fitted photosphere line was that of the young Sco-Cen stars. During this fitting procedure, objects with a *WISE* photometric fit reduced χ^2 greater than 4 in the relevant bands were excluded, as they are likely to be extended sources with poor photometry.

The criterion adopted for excess detection in the three colours was 8 per cent for $W_1 - W_2$, 13 per cent for $W_1 - W_3$ and 30 per cent for $W_1 - W_4$ above the expected photosphere line, plus the error on the *WISE* photometry. These detection thresholds were chosen conservatively such that the detections are likely to be significant even if the photosphere fit is underestimated by 10 per cent. The colour–colour diagrams for the three *WISE* colours and the fits can be seen in Fig. 1.

Given excess detections in the three *WISE* colours, we can remove from the sample those stars with suspect photometry. There were 19 objects with a detected excess in $W_1 - W_2$ only, three in $W_1 - W_3$ only, and three in $W_1 - W_2$ and $W_1 - W_4$ only. The 19 objects which show an excess only in the $W_1 - W_2$ colour are likely caused by the saturation behaviour of the *WISE* photometry fits. When partial saturation occurs in band W_2 (brighter than 6.5 mag), the *WISE* photometry fitting procedure produces a systematic overestimation of the flux (Cutri et al. 2011). All 19 of these objects are in the W_2 magnitude range where flux overestimation is expected and hence we have treated these objects in our sample as having no detectable excess. In addition, we remove those objects with poor photometry fits ($\chi^2 > 4$) in the W_1 and W_4 bands, as the remainder of the analysis makes use of the $W_1 - W_4$ excess only; there were 95 such objects. HIP 77562 and HIP 81891, which only show an excess in $W_1 - W_3$, both have poor photometry fits in band W_4 , and so are removed from the sample. HIP 77911 shows a poor photometry fit in the W_1 band ($\chi^2 = 4.6$), which is only marginally above our cut ($\chi^2 = 4$). HIP 77911 also shows a strong excess in the $W_2 - W_4$

colour, where the photometry fits are reliable, and hence we have included HIP 77911 in our sample with a 22 μm excess.

The *WISE* images of the 173 objects with detected excesses were then visually inspected for the presence of close, unresolved com-

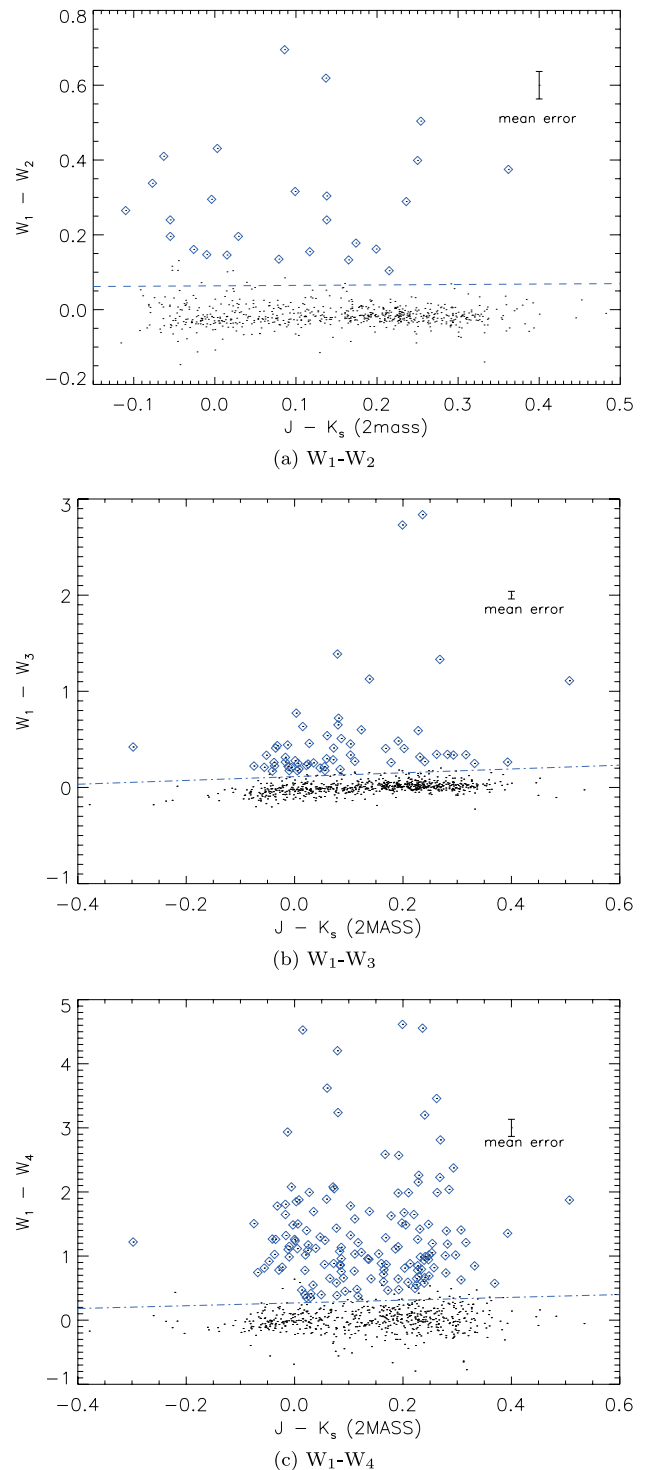


Figure 1. The colour–colour diagrams for the three *WISE* colours defined above. The blue line represents the corresponding excess detection threshold above which objects are considered to have a detectable excess. The photosphere grouping is clearly seen in each colour with fitted slopes and intercepts of (0.012, −0.18), (0.019, −0.018) and (0.22, −0.016), respectively. Blue diamonds indicate stars with detectable excesses.

Table 1. The *WISE* band fluxes as a multiple of the photosphere calculated from the three *WISE* colours and the 22 μm flux (complete table available online). The fluxes are in mJy.

HIP	p	F_{W_4}	$\sigma_{F_{W_4}}$	$R(W_2)$	$\sigma_{R(W_2)}$	$R(W_3)$	$\sigma_{R(W_3)}$	$R(W_4)$	$\sigma_{R(W_4)}$	Excess ^a	Subgroup
49360	6	12.02	0.76	0.99	0.03	0.98	0.03	1.03	0.07	NNN	LCC
50612	7	14.02	0.80	0.99	0.03	1.05	0.03	1.46	0.09	NNY	LCC
50667	7	11.54	0.71	1.01	0.03	1.23	0.04	2.24	0.15	NYN	LCC

^aThis column indicates the detection of an excess in the three colours.

panions and contamination from excess-producing nebulosity. This yielded 27 objects with excesses not likely to be caused by a disc. HIP 68413, HIP 79098 and HIP 76063, which have detectable excess in $W_1 - W_2$ and $W_1 - W_4$, but not $W_1 - W_3$, are included in the sample based on the image inspection. The lack of $W_1 - W_3$ excess associated with HIP 68413 is most likely due to a large error on $W_1 - W_3$, and the detected $W_1 - W_2$ excess associated with HIP 79098 was found to be caused by a clearly visible diffraction spike in the W_2 image. HIP 76063 has a W_2 magnitude of 5.6, and so the $W_1 - W_2$ excess associated with this star is most likely due to saturation. Finally, HIP 80897 shows a nebulous excess in $W_1 - W_3$ only, and so was removed from the sample. In total, we observe reliable excesses associated with 135 objects: 28 stars in US, 53 in UCL and 54 in LCC. The fluxes and excess ratios can be seen in Table 1.

4 DISCUSSION

The sources investigated in this study are BAF-type stars and hence the detected excesses are expected to be produced by dusty debris

discs rather than primordial gaseous discs (Carpenter et al. 2009). A clear outcome of our analysis is that the excess fraction in the three subgroups is not uniform with respect to membership probability (p). Fig. 2 displays the excess fraction in 10 per cent membership probability bins with $p > 20$ per cent. We have fitted linear trends to these data. Extrapolation to 100 per cent membership probability (i.e. certain members) along the linear fits results in excess fractions of 0.38 ± 0.1 , 0.33 ± 0.08 and 0.46 ± 0.13 for the three subgroups (see Table 2).

The extrapolated excess fraction for US is larger than the observed 24 μm excess fraction in the US sample used by Carpenter et al. (2009), which was found to be ~ 0.3 for B7-A9 stars and ~ 0.15 for F-type stars, and is in agreement with the value of ~ 0.33 for F- and G-type US stars seen by Chen et al. (2011). For associations at the age of UCL and LCC (16 and 17 Myr), Chen et al. (2005) reported a 24 μm excess fraction lower bound of ~ 0.35 , and Rieke et al. (2005) and Su et al. (2006) observe that 60 per cent of young stars (< 30 Myr) do not have an excess. These results are consistent with our study. We do not see an increase in the 22 μm excess fraction

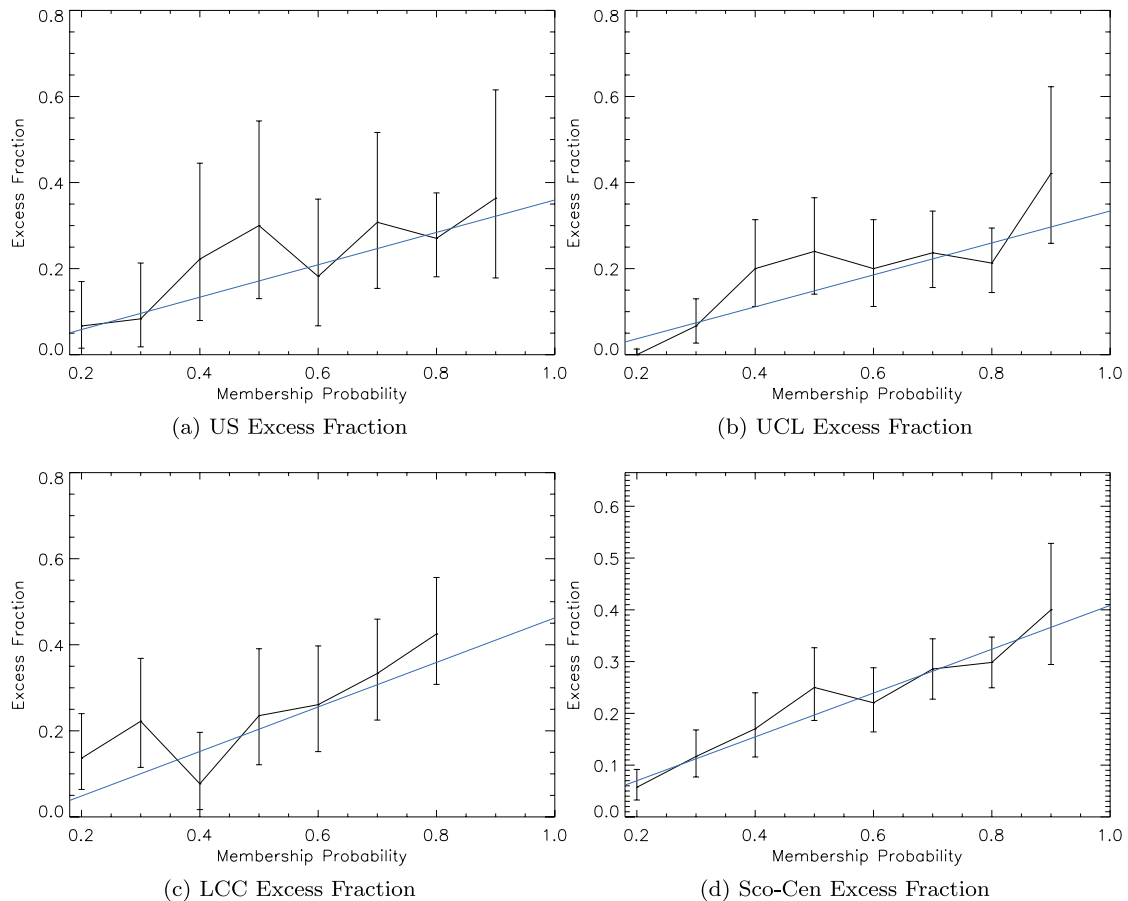


Figure 2. Excess fraction as a function of membership probability for the three subgroups and the entire association.

Table 2. The excess fraction fits for the seven graphs. The fitting was done to the equation $y = (a - b)p_{\text{mem}} + b$, where a and b are the excess fractions at $p_{\text{mem}} = 1.0$ and 0, respectively.

Figure	a	b	Corr	χ^2
US	0.38 ± 0.10	-0.02 ± 0.09	-0.65	0.6
UCL	0.33 ± 0.08	-0.04 ± 0.06	-0.68	2.2
LCC	0.46 ± 0.13	-0.05 ± 0.11	-0.77	3.3
All	0.41 ± 0.05	-0.02 ± 0.04	-0.65	1.3
B	0.18 ± 0.10	0.09 ± 0.10	-0.73	0.5
A	0.45 ± 0.11	0.05 ± 0.09	-0.61	2.2
F	0.47 ± 0.09	-0.08 ± 0.04	-0.77	2.8

for the two older subgroups (UCL, LCC). Previous observations have provided some evidence for a peak in the excess fraction as stars age from <10 to the 10–30 Myr age range (Currie, Plavchan & Kenyon 2008; Gáspár et al. 2009). However, our analysis shows that in the Sco-Cen association, the excess fraction does not change significantly between the three subgroups. A recent study (Pecaut, Mamajek & Bubar 2011) suggests that the true age of US may in fact be ~ 11 Myr, which offers a potential explanation for the lack of an excess fraction increase between the subgroups.

Given the lack of statistically significant differences in excess fraction between the three Sco-Cen subgroups, the association as a whole can be explored. Fig. 2(d) displays the linear excess fraction trend for combined sample. The extrapolated excess fraction was 41 ± 5 per cent for certain members, and consistent with 0 per cent for field stars, with a χ^2 of 1.3 for the fit.

We have cross-checked our sample with those of the *Spitzer* MIPS studies of Chen et al. (2005, 2011), Carpenter et al. (2009) and Su et al. (2006) as a basic assessment of the relative success of the *WISE* photometry in identifying excesses. We see that of those stars in both data sets which passed our photometry tests, six have observed excesses above 30 per cent in the MIPS sample but are not assigned an excess in our study. Of these six stars, five have measured $22 \mu\text{m}$ flux as a multiple of the photosphere within 1σ of the corresponding MIPS $24 \mu\text{m}$ values. The remaining star, HIP 79673, has a *WISE* flux ratio of 1.23 ± 0.15 , while the MIPS value is 1.53 ± 0.05 . Chen et al. (2011) indicate that the MIPS photometry for this star is contaminated, and the *WISE* image shows significant contamination in the form of well-resolved extended emission. This is most likely the cause of the discrepancy. Furthermore, there are two sources with large MIPS flux ratios (5–10 times the photosphere) which did not pass our photometry tests. HIP 61087 has very poor *WISE* photometry fits as well as clear contamination in the images (and in the MIPS data), though the measured flux ratio is similar to that of Chen et al. (2011). The presence of an excess cannot be made clear from the data and so no further comments on this object can be made. Finally, HIP 80921 shows a relatively strong excess; however, inspection of the images clearly shows that the excess is caused by extended emission. Similarly, the *Spitzer* MIPS images show extended emission with no clear stellar source at $24 \mu\text{m}$.

The correlation between the presence of a circumstellar disc and membership of the Sco-Cen association is clearly demonstrated in this analysis. It is thus important to consider stars with a detectable $22 \mu\text{m}$ excess which have lower membership probabilities ($p < 50$ per cent). In the latest Sco-Cen membership study (Rizzuto et al. 2011), a number of de Zeeuw et al. (1999) member stars were assigned low membership probabilities due to inconclusive proper motion data and the lack of a radial velocity measurement. Un-

Table 3. The 25 excess detections around low probability members and the adjusted probabilities.

HIP	p	HIP	p	HIP	p	HIP	p
51169	57	51203	71	53524	81	55616	46
60183	69	62482	59	62488	72	63236	76
63395	58	72099	81	76223	81	76782	75
77315	80	77523	70	78198	76	78357	49
78826	79	78943	82	80019	64	80458	82
81316	77	82154	48	83232	36	84881	43
86853	50						

resolved multiplicity has long been recognized as an important pitfall in kinematics-based association membership selection methods. An equal-mass binary system at the distance of Sco-Cen can produce a proper-motion offset of the order of ~ 2 mas from the true centre-of-mass motion. This is approximately the size of the uncertainties in the proper motion (van Leeuwen 2007), indicating that binary association members can be overlooked. The presence of a circumstellar disc can then be used to indicate membership for stars spatially and photometrically consistent, but kinematically inconsistent, with the Sco-Cen subgroups. We thus increase the Bayes' factors (see Rizzuto et al. 2011) of stars with between 10 and 50 per cent membership probability and a detected excess by a conservative factor of 4.8 (Table 3). This is the lower bound of the 99 per cent confidence interval of the ratio of excess fractions at 100 and 0 per cent membership probability. Note that including these stars in a sample of Sco-Cen members will necessarily introduce a bias towards disc presence.

The subgroup LCC has an anomalous concentration of stars with detectable excess in the 5–10 per cent membership probability range. Three of these stars, HIP 50612, HIP 52867 and HIP 53992, are known members of the young open cluster IC 2602, which is on the far side of LCC (Robichon et al. 1999) and are thus expected to have low Sco-Cen membership probabilities. Confusion with young background sources for this subgroup, which is on the Galactic plane, further contributes to the anomalous high excess fraction.

We have examined the excess fraction properties of our sample in three colour ranges: ($-0.3 < B - V < 0$), ($0 < B - V < 0.3$) and ($0.3 < B - V < 0.6$). These groupings correspond approximately to B-, A- and F-type stars according to the colour tables of Allen & Cox (2001). Fig. 3 displays plots of the excess fraction against

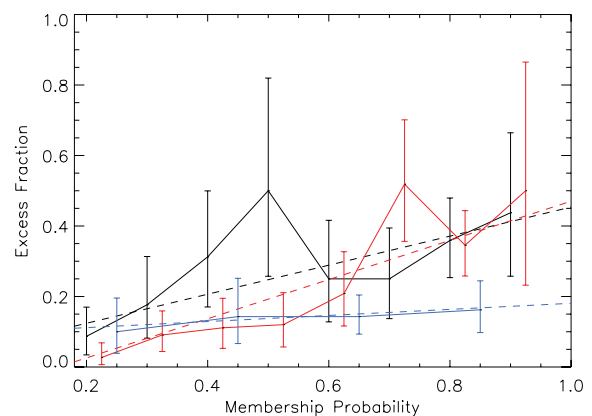


Figure 3. Excess fraction against membership probability for A-type (black), F-type (red) and B-type (blue) stars in our sample. The dashed lines represent the linear fits.

membership probability for the three spectral type ranges. We find the extrapolated excess fractions for the A- and F-type stars to be 45 ± 11 and 47 ± 9 per cent, while the B-type stars in our sample show no evidence of a trend in excess fraction with membership probability. The study of Carpenter et al. (2009) also found that A- and F-type stars have similar excess fractions at the age of Sco-Cen, with a small increase in excess fraction for the earlier spectral types. However, the earliest star included in the Carpenter et al. (2009) sample is B7, and so no direct comparison can be made to the bluest end of our sample.

5 SUMMARY AND CONCLUSIONS

We have analysed the available preliminary *WISE* photometry for the Sco-Cen stars of the Rizzuto et al. (2011) membership list and detected 135 $22 \mu\text{m}$ excesses above the expected photosphere emission. We have used Sco-Cen membership probabilities to extrapolate an excess fraction for certain members, and observe that there is no significant difference in excess fraction between the three association subgroups. This agrees with previous studies (Carpenter et al. 2009) and may be explained by the revised US age of ~ 11 Myr (Pecaut et al. 2011). Importantly, we find that the excess fraction is significantly lower for the B-type stars in our sample compared to A- and F-type association members, which is contrary to the trend seen by Carpenter et al. (2009). It is possible that the lack of a clear trend for the B-type sample could indicate that most of them are in fact young Sco-Cen members despite their kinematics. Another possible explanation relates to multiplicity. B-type stars have a significantly higher multiplicity fraction compared to later type stars (Kouwenhoven et al. 2005). The presence of a companion can potentially truncate the inner regions of the circumstellar disc through resonances (Artymowicz & Lubow 1994), producing a smaller disc fraction. This has been observed in a recent study of binaries in Taurus-Auriga, particularly with close (< 40 au) companions (Kraus et al. 2012). Among the highest probability members in our sample (> 90 per cent), there are six close (< 100 au) multiple systems without disc detections and one close multiple system with a detected excess. A closer, more comprehensive, comparison between disc presence and multiplicity information for the Sco-Cen B-type stars may shed light on this issue, but is beyond the scope of this study.

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