Dust discs around intermediate-mass and Sun-like stars in the 16 Myr old NGC 1960 open cluster

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ABSTRACT

We present an analysis of Spitzer IRAC (3.6–8 μm) and MIPS (24 μm) imaging of members of the 16±5 Myr old open cluster NGC 1960 (M36). Models of terrestrial planet formation indicate that rocky planets are likely to achieve their final masses at around 10–30 Myr, and thus this cluster is at an interesting epoch for planet formation. We find 21 B–F5 type stars and 14 F6–K9 type stars which have 24 μm excess emission, and thus determine that >30 per cent of B–F5 type stars and >23 per cent of F6–K9 type stars in this cluster have 24 μm excess emission. These excess frequencies are similar to those observed in other clusters of similar age. Three early-type stars have excesses at near-infrared wavelengths. Analysis of their spectral energy distributions confirms that these are true debris discs and not remnant primordial or transitional discs. None of the 61 Sun-like stars has confirmed near-infrared excess, and we can place a limit on the frequency of 8 μm excess emission around Sun-like stars of <7 per cent. All of the detected excesses are consistent with emission from debris discs and are not primordial.

Key words: circumstellar matter – open clusters and associations: individual: NGC 1960 – infrared: stars.

1 INTRODUCTION

Most young (1–2 Myr old) stars are surrounded by a gas-rich primordial disc with dust producing high levels of emission in the infrared (FIR/F, ≥ 0.1, e.g. Kenyon & Hartmann 1995). These are the birthplaces of planets. Current models of extrasolar planet formation propose that dusty discs around a new star settle, and km-sized planetesimals aggregate on a short (<1 Myr) time-scale (Weidenschilling & Cuzzi 1993). The largest planetesimals undergo runaway accretion followed by oligarchic growth resulting in tens or hundreds of 1000-km-sized bodies in their own cleared ‘feeding zones’ (Klahr 2008). These phases may take up to a few million years. Circumstellar gas accretes on to the star or on to large protoplanetary cores to create gas giant planets (Hartmann et al. 1998). Finally, these planetary embryos collide and merge in a chaotic growth phase to form a few stable terrestrial planets over 10–100 Myr (see e.g. Weidenschilling 1977). These or other processes remove the primordial discs on time-scales of 3–7 Myr (Hernández et al. 2007; Hillenbrand 2008; Currie et al. 2009). By 10 Myr almost all the remaining discs are optically-thin debris discs (see e.g. Wyatt 2008, and references therein). Emission from such discs arises from second-generation dust populations produced in collisions between planetesimals. These dust grains absorb and re-radiate starlight at wavelengths typically >10 μm.

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The Spitzer Space Telescope has been used to study the evolution of debris discs in a statistical manner (see e.g. Rieke et al. 2005; Su et al. 2006; Siegler et al. 2007; Rebull et al. 2008; Carpenter et al. 2009). These studies have tried to answer the question of why two apparently similar stars can have very different levels of excess emission. To date, the clearest dependency is on age. In A- and early-F-type stars, there is evidence for a peak in the upper envelope of excess emission at 10–20 Myr before a decay in proportion with time (see e.g. Wyatt 2008, and references therein). For solar-type stars, the number of observed objects is smaller and so correlations are harder to establish. Based on current evidence, the decay of 24 μm excess around solar-type stars appears to follow a similar pattern to the A-type stars but on a time-scale that is an order of magnitude shorter (a drop from 40 to 20 per cent of stars with 24 μm excess occurs between 10 and 100 Myr for solar-type stars, and between 100 and 500 Myr for A-type stars, see fig. 6 of Siegler et al. 2007). In general, the levels of excess emission are also smaller around lower mass objects (less than two times the photospheric flux) apart from around some of the youngest sources. These results can be interpreted within the framework of the evolutionary models of Kenyon & Bromley (2005, 2006). These suggest that planetesimals take longer to form at 10–30 au around A-type stars than at ~1 au around G-type stars (assuming thermal equilibrium, an excess detected at ≥24 μm implies a temperature of 100–150 K, translating to dust orbital radii of 3–30 au around A- and early-F-type stars and 0.5–3 au around solar-type stars). Thus, there are copious dust-producing collisional events for 10–100 Myr during
planetesimal accretion around A-type stars. Around solar-type stars, 100-km-sized embryos may be complete within a few Myr, and thus subsequent observed debris is likely to have been produced in recent catastrophic collisions like the impact that formed the Earth–Moon system (see e.g. Canup 2004, and references therein). These massive collisions are seen in as peaks in the excess emission above a lower background of emission in simulations of planetesimal discs (see e.g. Kenyon & Bromley 2005). Other authors have found these collisions could ignite collisional avalanches in the disc, which are brighter in discs with high optical depths (large populations of small grains, Grigorieva, Artymowicz & Thébault 2007), and could lead to longer lived increased emission.

The observed peak in debris disc emission for A- and early-F-type stars (10–20 Myr) is an important epoch for terrestrial planet formation, as models and radiometric dating suggest that terrestrial planets reach their final mass within 10–30 Myr (Wetherill & Stewart 1993; Yin et al. 2002; Kenyon & Bromley 2006). Disc emission from this epoch could therefore provide a direct tracer of the frequency of terrestrial planet-forming collisions. Cluster samples at this age have already been the target of Spitzer campaigns. Clusters with published 24-μm Spitzer photometry include: the 16–17 Myr Sco-Cen association (∼20 stars across F and G spectral types, Chen et al. 2005b); the 27 Myr old IC 4665 cluster (73 stars, A to mid-K types, Smith, Jeffries & Oliveira 2011); NGC 2547 at 35–40 Myr old (Naylor & Jeffries 2006; photometry for ∼70 sources); NGC 2232 at 25 Myr (209 sources of B–M type but only 38 have published 24 μm excess, Currie, Plavchan & Kenyon 2008b); and h Persei and χ Persei at 13 Myr (616 sources, spectral types B–G but uncertain membership lists, Currie et al. 2008a). It is difficult to obtain sufficient statistics from individual clusters to examine model predictions (either due to uncertain memberships or issues with obtaining sufficient 24-μm photometry). Combining open cluster data is the primary method of studying factors such as the influence of stellar mass on the incidence of debris discs at the epoch of terrestrial planet formation. As open clusters provide a homogeneous, chemically uniform coeval population, studies of multiple open clusters allow tests of how environmental factors influence debris emission, and the planet-forming processes that create it.

NGC 1960 (M36) is a young open cluster, with an age determined by isochrone fitting of 16$^{\pm}$10 Myr (Sanner et al. 2000). The large error bars on this value are a reflection of the difficulty in determining the age of this cluster as it has no known significantly evolved stars. Other recent age estimates in the literature include an age of ∼20 Myr (Mayne & Naylor 2008) and 25 Myr (Hasan 2005). As these are within the errors given by Sanner et al. (2000), we adopt an age of 16$^{\pm}$10 Myr in this paper. The cluster lies at a distance of 1318 ± 120 pc and has a reddening of $E(B-V) = 0.25 \pm 0.02$ mag (Sanner et al. 2000). This cluster provides an ideal complement to the studies of NGC 2232, and h and χ Persei as it lies between these clusters in age. Combining the studies of these clusters will allow us to place constraints on the evolution of debris discs within the peak of debris disc emission itself. It is also worth noting that this cluster can be viewed as an older analogue of the Orion Nebula Cluster (ONC). Integrating a Kroupa mass function (Kroupa 2001) and noting that there are ∼30 objects with masses of 3–7 M⊙ (using a distance modulus of $(m-M)_0 = 10.6 \pm 0.2$ mag and extinction of $A_V = 0.8$ (Sanner et al. 2000), and finding objects with absolute magnitudes $\sim -1.4$ to 0.79, see target selection in the next section), there are ∼445 stars with masses 0.5–7 M⊙ and ∼1680 stars with masses 0.1–7 M⊙. These numbers are comparable with the ONC. We would also expect 14 stars more massive than 7 M⊙ and find 16 stars of this size in NGC 1960 (see target selection in the next section), which is also comparable to the ONC.

In this paper, we present Spitzer archive data of NGC 1960. We use IRAC and MIPS 24-μm photometry to identify excess emission around cluster members based on $K_s \sim [24]$ versus $V - K_s$ colours and spectral energy distribution (SED) fitting. We discuss how levels of excess compare with other cluster samples at this epoch, and how these observations constrain models of terrestrial planet formation.

2 NGC 1960 TARGETS

To identify bright target members of the cluster, we used the sample presented by Sanner et al. (2000) and adopt the same proper motion and colour membership criteria presented in that paper. From their initial sample of 864 stars with B- and V-band photometry, 121 sources were found to have proper motions consistent with cluster membership (within 3σ of the central cluster proper motion, $2.9 \pm 2.7$ mas yr$^{-1}$ in RA, $-8.0 \pm 2.5$ mas yr$^{-1}$ in Dec.). Proper motion detections were considered accurate for sources with $V < 14$ mag, and thus we adopt this brightness as a cut-off for membership from this catalogue ($V = 14$ translates into a spectral type of ~G0 for this cluster). As a further test of cluster membership, the $B - V$ versus V colour–magnitude diagram of the targets is compared to a 16-Myr-old isochrone from Siess, Dufour & Forestini (2000) with $E(B-V) = 0.25$ mag (as determined by isochrone fitting in Sanner et al. 2000). The colour–magnitude diagram is shown in Fig. 1. This led to the rejection of seven targets with $V < 14$ and a final selection of 63 targets. We extract $K_s$ magnitudes for the targets from the 2MASS catalogue (Skrutskie et al. 2006). This source list is given in Table 1.

A set of lower mass members of NGC 1960 were assembled from the spectroscopy obtained at the William Herschel 4.2-m telescope. A separate paper is being prepared using these data, but the details relevant to this paper are given below. Observations were performed on 2009 November 25 and 26, and 2010 November 12–14 using the AF2/WYFFOS multifibre spectrograph, with an echelle grating that provided a spectral coverage of 420 Å centred at 6600 Å and a resolving power of 11 000. Targets with $14 < V < 18.5$ were selected from a $V - I$ colour–magnitude diagram, constructed using a BVI photometric survey performed at the Isaac Newton Telescope.
We conclude that this sample of low-mass cluster candidates has <10 per cent contamination.

For both the bright and lower mass samples, temperatures are estimated using the $V - K_s$ colours of the targets using the relation $T_{\text{eff}} = 5.55 + 0.195(V - K_s) + 0.013(V - K_s)^2$ (Alonso, Arribas & Martínez-Roger 1996). Colours were first dereddened using $E(B - V) = 0.25$ (Sanner et al. 2000) and conversions to $E(V - K_s)$ from Rieke & Lebofsky (1985). For some of the higher mass targets (spectral type earlier than F0), a relation in $B - V$ is more often preferred to approximate temperature. Using the relation $B - V = -3.684 \log T_{\text{eff}} + 14.551$, we find temperatures that can be lower by up to 10 per cent for the highest mass targets. In this paper, temperature is only used to determine colour corrections on the photometry. Within the $\sim 6000$–11 000 K temperature range of the higher mass targets, this translates into a maximum difference in aperture correction factor of <0.5 per cent.

### 3 SPITZER DATA

Data were sourced from the Spitzer Heritage Archive. Data were taken with the IRAC (Fazio et al. 2004) and MIPS (Rieke et al. 2004) instruments under Spitzer Programme 50265. IRAC data were obtained on 2008 October 23 in high dynamic range mode using a $6 \times 8$ mapping array. The Astronomical Observation Request (AOR) consists of 260-arcsec map steps, array orientation and a five-point Gaussian dither with small scalefactor. A frame time of 12-s exposures gave a 5σ point-source sensitivity of 17.4, 16.6, 15.7 and 14.8 mag in the four IRAC bands (3.6, 4.5, 5.8 and 8 μm, respectively).

MIPS data were obtained on 2008 November 1 in scan-mapping mode centred at $5^h 36^m 12.2^s, +34^\circ 08.24^\prime$. A medium scan rate, scan leg length of 0.5 and 11 scan legs were used to cover an area of $38 \times 55$ arcmin$^2$. Five repetitions of the AOR were obtained, giving a 5σ point-source sensitivity of 11.4 mag at 24 μm.

The data were extracted as basic calibrated data files from the archive. These data are individually flux calibrated array images. The Spitzer Science Center MOPEX package (Makovoz & Marleau 2005) was used to produce the final mosaics. We used standard MOPEX modules. The individual 24-μm MIPS frames were flat-fielded using the flat-field module in MOPEX. Overlap correction was determined using the default settings in the overlap module, and the final image mosaic consisting of all five repetitions of the AOR was constructed using the mosaic module. Mosaics were created for each of the IRAC channels using the overlap and mosaic modules in MOPEX with default settings. For details of these modules, see Makovoz & Marleau (2005) or the online MOPEX User’s Guide at http://ssc.spitzer.caltech.edu/dataanalysistools/tools/mopex/mopexusersguide/. Photometry was extracted using the APEX package from MOPEX. For the IRAC channels, the point spread function (PSF) is undersampled and thus photometry was extracted in circular apertures of radius 3 pixels ($\sim 3.6$ arcsec) with background determined in an annulus of inner radius 12 pixels and outer radius 20 pixels ($\sim 14.4$–24 arcsec). Apertures were centred on the location of each source as listed in Tables 1 and 2. Of the 132 targets in the full sample, four (two, four, two) fell outside the channel 1 (2, 3, 4) imaging mosaics, respectively. Array location-dependent corrections were applied to the IRAC photometry. Correction images available online at http://ssc.spitzer.caltech.edu/irac/calibrationfiles/locationcolor/ were mosaicked in the same way as the data frames to produce a correction mosaic. The aperture photometry of a source was then
Table 3. Spitzer IRAC and MIPS 24-µm photometry for bright members of NGC 1960. Only a few rows are shown here to illustrate the content; the full table is available online (see Supporting Information).

| Source | [3.6]  | [4.5]  | [5.8]  | [8.0]  | [24]  | $K_S - [24]$ | $F_{24}/F_{phot}$ | Comment |
|--------|--------|--------|--------|--------|--------|--------------|-----------------|---------|
| 1      | 8.909  | 8.844  | 8.876  | 8.966  | 8.918  | -0.183       | 0.906           |         |
| 2      | 8.985  | 8.953  | 8.990  | 9.061  | 8.784  | 0.048        | 1.122           |         |
| 3      | 8.968  | 8.934  | 8.993  | 9.034  | 9.129  | -0.283       | 0.826           |         |
| 4      | 8.106  | 7.709  | 7.549  | 7.310  | 6.262  | 2.152        | 7.424           | XS      |
| 5      | 9.154  | 9.110  | 9.147  | 9.221  | 9.259  | -0.261       | 0.845           |         |
| ...    | 11.140 | 11.122 | 11.186 | 11.254 | 11.453 | <0.410       | 0.423           | Contam. |

Notes. Stars which had contaminating flux of more than 13 per cent subtracted from the aperture photometry are marked as ‘Contam.’ in the Comment column. None of these targets has been identified as having confirmed 24 µm excess. Sources with $K_S - [24]$ more than 3σ higher than the photospheric relation from Plavchan et al. (2009) are marked as ‘XS’ (excess sources) in the Comment column. The error on the photospheric relation includes differences from different photospheric predictions, variation in the colours observed for sources without excess and statistical error on the 24-µm photometry added in quadrature as described in the text.

Table 4. Spitzer IRAC and MIPS 24-µm photometry for low-mass members of NGC 1960. Only a few rows are shown here to illustrate the content; the full table is available online (see Supporting Information).

| Source | [3.6]  | [4.5]  | [5.8]  | [8.0]  | [24]  | $K_S - [24]$ | $F_{24}/F_{phot}$ | Comment |
|--------|--------|--------|--------|--------|--------|--------------|-----------------|---------|
| 1_136  | 12.621 | 12.645 | 12.679 | 12.726 | 11.940 | <0.715       | 1.890           |         |
| 1_138  | –      | 12.935 | –      | 13.312 | 11.886 | 1.134        | 2.851           | XS      |
| 1_151  | 12.809 | 12.810 | 12.832 | 12.838 | 11.385 | 1.499        | 3.958           | XS      |
| 1_223  | 13.254 | 13.272 | 13.284 | 13.508 | 12.007 | <1.206       | 2.964           |         |
| 1_371  | 13.580 | 13.486 | 13.626 | 13.828 | 11.930 | <1.720       | 4.623           |         |
| ...    |        |        |        |        |        |              |                 |         |

Note. See notes in Table 3 for the description of the Comment column.

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were \( F_{8\mu m}/F_{24\mu m} = 4.57 \pm 3.56 \). Any sources within 20 arcsec of our target detected at 24 \( \mu \)m had their contamination calculated, the contaminating source was then removed from the list of detected sources at 8 \( \mu \)m, and then the residual 8-\( \mu \)m-detection list was checked for sources within 20 arcsec of the target. The flux of these sources was divided by 4.57 to get the 24-\( \mu \)m flux and the contamination in the target aperture calculated as above. The median and mean absolute deviations of the contamination of the targets are \( 7 \pm 6 \) per cent of the aperture flux. Sources with high levels of contamination (\( > 13 \) per cent, \( > 1\sigma \) higher than average) or with other issues that could affect their photometry (e.g. high number of bad pixels, close to the edge of the mosaic) are listed in Table 4. PRF photometry should mitigate against the effects of source contamination through the active deblending algorithm, and so we do not include a contamination correction for sources with PRF photometry. We used the above steps to determine the levels of contamination that would have been seen in aperture photometry for those sources with PRF photometry. This was used as a method of checking that there could be no sources in the IRAC 8-\( \mu \)m mosaic that might have been blended with the target in the lower resolution 24-\( \mu \)m mosaic. In all cases, the possible contamination was \( \leq 1 \) per cent of the PRF photometry.

After subtracting the contaminating flux from the MIPS 24-\( \mu \)m photometry, an aperture correction of 0.433 mag determined from bright targets was applied. A colour correction was applied for each target by interpolation from values tabulated in the MIPS Data Handbook. We used the zero-point of 7.14 Jy listed in the handbook to convert the fluxes into magnitudes. Photometric errors for MIPS 24-\( \mu \)m observations are 4 per cent (Engelbracht et al. 2007). We added this in quadrature to statistical errors returned by the aperture/PRF photometry APEX modules, arising from pixel-to-pixel variations, to give a final error on the flux. The final MIPS photometry is listed in Tables 3 and 4. Of the 132 targets in the sample, two fall outside the 24-\( \mu \)m mosaic (2_195 and 2_277). These targets also fall outside the field of view in the IRAC images, and therefore they are not included in the table.

4 DETECTION OF EXCESS EMISSION

4.1 Near-infrared excess

The sensitivity of the IRAC data allows the detection of photospheric emission down to the levels of photospheric emission of M dwarfs at the distance of NGC 1960 (\( \sim 1300 \) pc). Thus, all the targets which fall within the IRAC fields of view are detected with good signal-to-noise ratio (\( > 5 \)).

To determine if there is any excess emission in the IRAC photometry from the target stars, we plot the \( Ks - [3.6], Ks - [4.5], Ks - [5.8] \) and \( Ks - [8.0] \) colours against \( V - Ks \). This method has been used in other clusters to search for near-infrared excess (see e.g. Gorlova et al. 2007; Currie et al. 2008a; Smith et al. 2011). These plots are shown in Fig. 2.

The plots show that the majority of targets have colours consistent with photospheric emission. The crosses mark the targets in Table 1 and the diamonds mark the sources listed in Table 2. Errors on the \( Ks - \) IRAC colours are taken from the pixel-to-pixel variation in the background apertures in the IRAC photometry plus the 3 per cent maximum calibration error typical for IRAC photometry (Reach...
et al. 2005), added in quadrature to the errors on the $K_s$ photometry from the 2MASS. In order to identify sources with unusual colours, we adopt the following procedure. For each target, we identify other targets in the sample with similar $V - K_s$ colours [within $\delta(V - K_s) < 0.25$]. The mean $K_s$ - IRAC colour for these targets is calculated, together with the error (standard deviation of the $K_s$ - IRAC colours added in quadrature to the mean error on the colour calculated as described above). Any targets with colours differing from the mean of other targets with similar $V - K_s$ by more than three times this error are identified and removed from the source list. This process is repeated until no sources with colours different from the average by more than three times the error are found. The outlier sources are labelled in the figures.

From the IRAC colours, we identify bright targets 4 and 8 as having colours consistent with excess emission in all four IRAC bands, bright target 14 as having colours consistent with excess emission in the bands [4.5], [5.8] and [8.0], and lower mass stars 4_336 and 4_536 as having colours consistent with excess in the two longest IRAC wavebands. None of these targets is highlighted in the 2MASS catalogue as having uncertain $K_s$ photometry.

Bright target 16 has colours that appear to be consistent with excess emission in the two longest IRAC bands ($K_s - [5.8] = 0.133 \pm 0.038$ and $K_s - [8.0] = 0.249 \pm 0.039$), although in the $\sigma$-clipping algorithm described above these colours are at the 2.3 and 2.1$\sigma$ levels of significance. Constructing an SED for this object using a Kurucz model profile for the appropriate temperature (9900 K, see Table 1) and scaling to a best fit for the 2MASS $JHK_s$ photometry, we find the IRAC channel 3 and 4 photometry to be consistent with photospheric emission within 2 and 3$\sigma$, respectively. Fitting a blackbody to the IRAC and MIPS photometry of the source shows that any excess must be at a maximum temperature of 600 K (in order to not exceed limits from the IRAC photometry). This corresponds to a minimum radial location of 0.67 au assuming the emitting grains behave like blackbodies. However, as the IRAC photometry is consistent with a photospheric emission within the errors, we cannot confirm that this target exhibits true near-infrared excess.

4.1.1 Contamination by other sources

Target 4_536 lies very close to bright target 8. In the IRAC channel 4 data (8 $\mu$m), the emission from bright target 8 extends to the location of target 4_536, and so the target may have contaminated flux. This is also true in the IRAC channel 3 image, although the emission from bright target 8 is less extended in this image. As the resolution is higher for the lower wavelength channels, this is not the case in the channel 1 and channel 2 images. Thus, we cannot confirm excess for this target in the IRAC bands. This target is not detected at the 3$\sigma$ level in the MIPS 24-$\mu$m imaging, and so we have no other photometric measurements to further test whether this target exhibits true excess emission.

Target 4_336 lies very close to a bright infrared source (detected in the IRAC images at 84:02458 in RA, 34:103 in Dec.). This source has been identified as IRAS 05327+3404, a probable pre-main-sequence K2 class II/III star with a large optically-thick circumstellar disc producing a large infrared excess (not thought to be related to NGC 1960, Magnier et al. 1999). In the high-resolution data (IRAC channels 1 and 2), this source can be seen as separate from target 4_336. However, in IRAC channels 3 and 4 and the MIPS 24-$\mu$m images, the bright source IRAS 05327+3404 extends to cover the location of target 4_336. We can therefore only provide upper limits to the flux for this target in IRAC channels 3 and 4, and in the MIPS 24-$\mu$m photometry.

4.1.2 True excess

Bright targets 4, 8 and 14 (BD +34°·1113, BD +34°·1110 and BD +34°·1098, respectively) are amongst the highest mass stars in our sample, as indicated by their colour in $V - K_s$ and temperature inferred from $B - V$. These sources show evidence for excess emission in the near- and mid-infrared (see Table 3 and Fig. 2). We checked these sources did not have significant contamination using the method described in Section 2. We construct SEDs for these objects using Kurucz model profiles for the appropriate temperature for each source (see Table 1) scaled to a best fit to the $JHK_s$ 2MASS photometry using a $\chi^2$ analysis. These plots (Fig. 3) show that the near-infrared slopes are not consistent with photospheric emission alone. We can fit the IRAC and MIPS photometry by adding a single-temperature blackbody to the photospheric emission for bright sources 4 and 8. These fits are at the temperatures of 800 and 900 K, respectively (equivalent to dust lying at radii of 0.73 and 0.36 au, respectively, assuming the material emits as a blackbody). For bright target 14, the IRAC and MIPS photometry cannot be fitted by a single-temperature blackbody, and so we adopt two blackbody contributions at temperatures of 600 and 180 K to fit the emission (0.73 and 8.06 au, respectively). It should be noted that this illustrative fit is non-unique and that longer wavelength photometry would be required to determine constraints on the cooler blackbody temperature in particular. In all three plots, the blackbody contributions are shown by a dotted line and the total (blackbody and photospheric emission) is shown by a dashed line (Fig. 3).

For all three targets with near-infrared excess, we must ask if this emission is evidence for a remnant primordial disc. At an age of 16 Myr for the cluster, such primordial discs would be rare as they are expected to dissipate on time-scales of a few Myr (see Wyatt 2008, and references therein). The fractional luminosity of these discs is much lower than we would expect for primordial disc emission. Adopting the blackbody fits to the emission shown in Fig. 3, we find that the excess emission has fractional luminosity $L_d/L_*$ = $3.9 \times 10^{-3}$ for both bright stars 4 and 8, and that the two components of the excess around bright star 14 have fractional luminosities of $L_d/L_*$ = $1.3 \times 10^{-3}$ and $2.7 \times 10^{-3}$ (for components at 600 and 180 K, respectively). These levels are consistent with $L_d/L_*$ < $10^{-2}$ which conventionally defines a debris disc as opposed to a primordial disc (Lagrange, Backman & Artymowicz 2000). These targets join a small but growing population of A-type stars with debris discs within 10 au (e.g. $\xi$ Lep, Moerchen et al. 2007; HD 172555, Rebull et al. 2008). Bright star 14 is one of a growing number of systems with evidence for multiple-component discs. 11 stars were identified by Chen et al. (2009) as having probable multiple-component discs, which have been interpreted as possible Solar system analogues (see also the $\beta$ Pictoris association member $\eta$ Tel, Smith et al. 2009).

4.1.3 Limits on near-infrared excess and primordial emission

As a further confirmation of the evolved nature of the targets observed in this study, we follow the example of Muzerolle et al. (2010) and consider the IRAC/MIPS SED slope for each of our objects as a method of identifying possible primordial/transition disc candidates. We consider the value of $\alpha = d \log v\nu/d \log \lambda$ over
IRAC channels 1 and 3 (so for $\lambda = 3.6$ and 5.8 $\mu$m, respectively) and over IRAC channel 4 and the MIPS ($\lambda = 8.0$ and 23.7 $\mu$m, respectively). We plot these spectral slopes for all stars in our study in Fig. 4, and plot upper limits to the spectral slope $\alpha_{8-24}$ for sources without significant photometry at 24 $\mu$m. According to the metrics of Muzerolle et al. (2010), stars with $\alpha_{3.6-5.8} > -1.8$ are possible primordial disc hosts. Stars with $\alpha_{3.6-5.8} < -1.8$ and $\alpha_{8-24} > 0$ are possible transition disc candidates, and may have optically-thick discs at >1 au with depleted/optically-thin inner holes. Target 4_336 appears to lie in the primordial disc region, but this object’s flux is highly contaminated by a known primordial disc candidate as discussed in Section 4.1.1, and therefore this is not a true detection of a primordial disc. Bright target 4 lies close to the boundary for possible primordial emission. Bright target 14 lies in the region of possible transition disc emission. However, for both these targets, we have shown that it is possible to fit their emission with optically-thin ($L_{IR}/L_\star < 10^{-2}$) blackbody emission. Thus, we find the emission for both these targets is consistent with debris disc emission. The remaining targets in our study all have $\alpha_{3.6-5.8} < -1.8$ and $\alpha_{8-24} < 0$, consistent with no excess or optically-thin emission.

For those targets with no evidence of significant near-infrared excess, we determine the limits we can place on excess emission in the IRAC photometric bands. Excluding the sources discussed above, we determine an empirical photospheric locus and uncertainty in $K_S - \text{IRAC}$ as a function of $V - K_S$. For each value of $V - K_S$, we determine the mean and median standard deviations of the $K_S - \text{IRAC}$ colours of sources with $V - K_S$ within 0.25 of this value. These are our empirical photospheric locus and error. We fit a linear model to the error to determine the $\sigma$ values for each colour. We determine the dispersions in the $K_S - \text{IRAC}$ colours to be $\sigma_{K_S - [3.6]} = 0.04 + 0.005(V - K_S)$, $\sigma_{K_S - [4.5]} = 0.04 + 0.01(V - K_S)$, $\sigma_{K_S - [5.8]} = 0.04 + 0.02(V - K_S)$ and $\sigma_{K_S - [8.0]} = 0.05 + 0.04(V - K_S)$. Adopting these uncertainties, we find that for an F5-type star ($V - K_S \sim 1$) we can place the following $3\sigma$ limits on excess emission in the near-infrared: $F_{3.6}/F_{\text{phot}} < 1.13; F_{4.5}/F_{\text{phot}} < 1.15; F_{5.8}/F_{\text{phot}} < 1.18; \text{and } F_{8.0}/F_{\text{phot}} < 1.28$. For objects with $V - K_S = 4$ (~M1 type), we place the following $3\sigma$ limits.

Figure 3. The SED of bright targets with significant excess emission in IRAC channels. The crosses mark Hipparcos V-band and 2MASS JHKs photometry. The diamonds mark IRAC and MIPS 24-$\mu$m photometry. A Kurucz profile of appropriate temperature for each source (see Table 1) is shown with a solid line. The dotted line marks blackbody fits to the excess emission, with the total (blackbody plus photospheric) emission indicated by a dashed line.

Figure 4. The spectral slopes for all targets in our study. Sources without significant detections at 24 $\mu$m are shown as upper limits to the spectral slope based on the $3\sigma$ upper limits to their flux. Regions of the spectral slope–parameter space which could indicate primordial (optically-thick) or transition discs are labelled. Most targets have spectral slopes consistent with no excess or optically-thin emission consistent with a debris disc (see text for more details).
limits on excess in the near-infrared: $F_{3.6}/F_{\text{phot}} < 1.18$; $F_{4.5}/F_{\text{phot}} < 1.25$; $F_{5.8}/F_{\text{phot}} < 1.39$; and $F_{8.0}/F_{\text{phot}} < 1.79$.

### 4.2 24-µm excess

The principal means of identifying debris discs is the detection of excess emission (above the levels expected from the photosphere) in mid-infrared ranges, and no detection of such an excess at near-infrared wavelengths (which may indicate a primordial or transition disc). The sensitivity of the MIPS observations of NGC 1960 allows a detection down to $\sim 12$th magnitude at 24 µm (3σ point source limit). This means we can only detect photospheres to A3V ($V - K < 0.10$), which means that for many of our targets, we would not expect to detect the photosphere. This is reflected in the results presented in Tables 3 and 4. Those sources with significant detections generally have high values of $K_S - [24]$ and $F_{24}/F_{\text{phot}}$ (detected emission at 24 µm/expected emission from the photosphere).

In order to determine which targets exhibit 24 µm excess, we follow the example of recent papers (e.g. Rebull et al. 2008; Stauffer et al. 2010) in using the targets’ $K_S - [24]$ colours. This method requires a well-defined model of photospheric colours. Stauffer et al. (2010) used Spitzer observations to determine an empirical relation for $K_S - [24]$ from $V - K_S$, defined as $K_S - [24] = 0.042 - 0.053 \times (V - K_S) + 0.023 \times (V - K_S)^2$. Similar relations have been presented by Gorlova et al. (2006), and Plavchan et al. (2009), who included M dwarfs in the spectral range covered. As the Stauffer et al. (2010) relation is only valid to $V - K_S < 3$ and our NGC 1960 sample includes sources of lower mass, we use the Plavchan et al. (2009) relation as our photospheric model.

In Fig. 5, we show the $K_S - [24]$ versus $V - K_S$ colours of the target sources. The crosses are used to mark the bright targets taken from Sanner et al. (2000), and the diamonds mark the sources identified as lower mass cluster members. Upper limits for targets with signal-to-noise ratio of less than 5 are marked in grey. Overplotted as a solid line is the expected photospheric colour from Plavchan et al. (2009). We determine the dispersion around this relation by considering the colours of the bright targets ($V - K_S < 0.1$) for which the photosphere should have been detectable. A histogram of the $K_S - [24]$ colours of these sources was constructed, and a Gaussian function fitted to the left-hand side of this function (the targets which are not likely to have excess emission). The best-fitting Gaussian FWHM was found to be 0.14. This dispersion includes the errors in $K_S - [24]$ (typically around 0.05 for targets with $V - K_S < 0.1$, see Table 3), and so we adopt this value as a minimum uncertainty on the photospheric values of $K_S - [24]$. We expect the errors on the $K_S - [24]$ colours to increase for fainter targets due to decreased signal-to-noise ratio. Using all significant detections (>5σ), we examined the errors on the 24-µm photometry as a function of $V - K_S$. We found that the effect of source colour on the uncertainty was relatively weak. This is because for most of the spectral range considered in this study we are detecting sources with excess emission only, and so the error levels were nearly constant. We determined a linear fit to the uncertainty (using a $x^2$ test) on $K_S - [24]$ and added this to the measurement of the dispersion adopted as a minimum uncertainty as discussed above. This gave us a final uncertainty on $K_S - [24]$ from our photometry of 0.14 + 0.032($V - K_S$). We also consider the differences between the photospheric colour models from Plavchan et al. (2009), Gorlova et al. (2006) and Stauffer et al. (2010). For each value of $V - K_S$, we interpolated the predicted $K_S - [24]$ for each model, and add the standard deviation of the three results in quadrature to the error relation already described. These errors are shown (at a 3σ level) by a dotted line in Fig. 5.

From this figure, we identify 17 of the targets from Table 1, and 18 of those from Table 2 as having significant 24 µm excess. These sources are identified in Tables 3 and 4 by a note in the comments column.

### 5 DISCUSSION

#### 5.1 Relationship with multiplicity

As the majority of stars are binary or higher order multiples (Abt 1983; Duquennoy & Mayor 1991), the relationship between stellar multiplicity and debris disc parameters has been the subject of much recent study. Cieza et al. (2009) presented an analysis of IRAC data from several Spitzer legacy surveys which showed that for projected separations of <40 au, systems were half as likely to retain their primordial discs as systems with larger separations (suggesting a disc lifetime of 0.3–0.5 Myr for close binaries compared to 3–5 Myr around single stars). Conversely, Trilling et al. (2007) found in their study of field stars (with most stars >600 Myr old) that the binary stars had a higher incidence of debris discs than single stars. Debris discs were found to be more common around binaries with small (<3 au) or large (>50 au) separations than around intermediate-separation binaries (3–50 au). This survey concentrated on detections at 70 µm, and so on discs that were farther from their host stars. Plavchan et al. (2009) found no evidence of the trend suggested by Trilling et al. (2007), and Duchêne (2010) found no significant dependence of debris disc incidence on binarity or binary separation. Stauffer et al. (2010) showed tentative evidence that in the 100-Myr Blanco 1 cluster, binary stars have a lower 24 µm excess frequency than single stars (adopting height above a single-star isochrone as a binarity proxy). They combine their results with data from the Pleiades (~100 Myr) and NGC 2547 (~35 Myr), and find an overall chance of 0.05 per cent that the excess around single and binary samples is drawn from the

![Figure 5. The $K_S - [24]$ versus $V - K_S$ colour–colour diagram for sources with $>3\sigma$ detections in the MIPS mosaic. The grey symbols mark upper limits for sources with $<3\sigma$ detections. The diamonds mark sources from the lower mass sample and the crosses mark additional sources from Sanner et al. (2000). Errors are the statistical and calibration errors on $[24]$ added in quadrature to the error on the 2MASS $K_S$ magnitude. The predicted photospheric colours from Plavchan et al. (2009) are shown with a solid black line. For most of the spectral range under consideration, only sources with significant excess are detected.](https://academic.oup.com/mnras/article-abstract/420/4/2884/971857)
same parent population [using a Kolmogorov–Smirnov (K–S) test]. In Smith et al. (2011), we showed that there was no evidence for a dependence of debris disc emission on stellar multiplicity in the 27-Myr-old open cluster IC 4665. We adopt the same analysis here using height above a single-star isochrone as a proxy for multiplicity and compare this to the Ks − [24] colour. The isochrone was tuned from a fit to the Pleiades following Stauffer et al. (2010). This is shown in the left-hand panel of Fig. 6. Bright star 4 (HIP 26354) stands out in this plot as having a very high V-band magnitude for its colour (V − Ks). This source has been identified as having high variability (δV = 0.281, LeFèvre et al. 2009) and therefore the target’s photometric measurements are dependent on the epoch of observation, a possible cause of the anomalously high V-band magnitude.

We expect that most targets will have \( V - V_{\text{pred}} \leq 0.75 \) (where \( V_{\text{pred}} \) is the predicted V-band magnitude of a star of a given V − Ks colour from the single-star isochrone). Sources with \( V - V_{\text{pred}} > 0.75 \) are possible triples or higher order systems. From our sample of 132 targets (from Tables 1 and 2), 26 targets are found to have \( V - V_{\text{pred}} > 0.75 \), giving a detection rate of \( 19^{+1}_{-1} \)% per cent higher order multiples. This is somewhat higher than is seen in other studies (\( \sim 9–12 \)% per cent, A02; A98; A09; D08; D07; A07), although not significantly so. This could also be reduced if we take into account errors on the 2MASS KS photometry, which means that at the 3σ level a minimum of 16 sources (12 per cent of the target list) have \( V - V_{\text{pred}} > 0.75 \), which agrees with the expected frequencies of higher order multiplicity. In general, we do not see any evidence for a relation between \( V - V_{\text{pred}} \) and \( Ks - [24] \) (see the right-hand panel of Fig. 6). We separate the sample into sources with \( V - V_{\text{pred}} \leq 0.3 \) and those with \( V - V_{\text{pred}} > 0.3 \), and compare the \( Ks - [24] \) colours of the two populations. Using a K–S test on the \( Ks - [24] \) excess for sources with significant 24-μm detections [where the excess is defined as \( (Ks - [24])_{\text{obs}} - (Ks - [24])_{\text{pred}} \), where \( (Ks - [24])_{\text{obs}} \) is determined from the Plavchan model for the photospheric colours], we find only a 70 per cent probability that we can reject the null hypothesis that the samples are drawn from the same population. We also compare the two samples (\( V - Ks \leq 0.3 \) and \( V - Ks > 0.3 \)) including the upper limits. We use the ASURV statistical package (LaValley, Isobe & Feigelson 1990) to compare the two populations using several tests (see Feigelson & Nelson 1985, for a description of the tests). We find that the probability of rejecting the null hypothesis (that the samples are drawn from the same population) is 0.47 according to the logrank test, and 0.74 according to the Peto–Prentice test. The differences in the probabilities arise from the different treatments of the upper limits in the methods. In either case, we see no evidence that the multiplicity of the stellar system affects the incidence of debris disc emission in this cluster.

5.2 Placing NGC 1960 into context

The NGC 1960 cluster is at an interesting age for planet formation. At 16 Myr, any gas giant planets are expected to have formed and the circumstellar disc evolved from a gas-rich to gas-poor state within ~3 Myr for high-mass stars (B, A and early F types, e.g. Hernández et al. 2005) or 5–7 Myr for low-mass stars (F5 or later type, e.g. Hernández et al. 2007). Terrestrial planet formation, on the other hand, is expected to continue for up to 100 Myr (e.g. Weidenschilling 1977). A peak in 24 μm debris emission at 10–20 Myr around A- and early-F-type stars can be interpreted as evidence of delayed stirring of the disc by the formation of Pluto-sized bodies at this epoch (see e.g. Kenyon & Bromley 2002). We now explore how NGC 1960 fits in with these models.

5.2.1 Excess emission at 24 μm

A ‘rise and fall’ in 24 μm excess emission (emission above expected photospheric levels) was first identified by Hernández et al. (2007) and Currie et al. (2008a). The peak levels of excess emission (defined as emission above that arising from the stellar photosphere) and frequency of excess are seen to rise from ~5 to 10 Myr, before falling after ~20 Myr around higher mass (A and early F type) stars. We examine NGC 1960 in the context of this pattern by comparing the rate of excess around the higher mass stars to other clusters of ages ≥5 Myr.

In Fig. 7, we show the frequency of excess emission for stars of spectral types B0–F5 observed with the MIPS. We include data for the following open clusters: ω Orionis (5 Myr, Hernández et al. 2009, 2010); Upper Scorpius (5 Myr, Chen et al. 2005a; Carpenter et al. 2009); Orion OB1b (5 Myr) and Orion OB1a (8.5 Myr, both Hernández et al. 2006); Lower Centaurus Crux (16 Myr) and Upper Centaurus Lupus (17 Myr, both Chen et al. 2005a); NGC 2232 (25 Myr, Currie et al. 2008b, note that only 38/209 stars have published MIPS 24-μm observations); IC 4665 (27 Myr, Smith et al. 2011); NGC 2547 (35 Myr, Gorlova et al. 2007); IC 2391 (50 Myr, 2009).
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Figure 7. The frequency of 24 µm excess emission of stars of spectral types B0–F5 as a function of age. Clusters are listed in the text and in Table 5. The datum for NGC 1960 is shown by the diamond and is offset in age to 18 Myr to avoid confusion with data from the Sco–Cen association.

Siegler et al. 2007); Blanco 1 (100 Myr, Stauffer et al. 2010); the Pleiades (115 Myr, Golrva et al. 2006); the Hyades (625 Myr, Cieza et al. 2009); and a collection of field stars (Bryden et al. 2006). For all clusters, we extract the spectral type for each object listed in the above papers. Where no spectral type is listed, we assign a spectral type based on the $V-K_S$ colour of the target. The relationship was determined from Kurucz model profiles of stars at typical temperatures for each spectral type (so F5 stars have $V-K_S \sim 1$, temperatures taken from Cox 2000). The frequencies are listed in Table 5. Clusters with less than 10 members in the spectral range B0–F5 were excluded from Fig. 7 but are listed in Table 5 and included in our examination of levels of excess emission below. Stars are identified as having excess emission if they satisfy the following criteria (following Currie et al. 2008b):

$$(K_S-[24])_{\text{obs}} - (K_S-[24])_{\text{pred}} \geq 3\sigma_{[24]} \tag{1}$$

and

$$(K_S-[24])_{\text{obs}} - (K_S-[24])_{\text{pred}} \geq 0.15, \tag{2}$$

Table 5. The excess frequencies of open clusters with published 24-µm MIPS photometry.

| Name         | Age (Myr) | Excess/total | B0–F5 | Per cent with excess | Excess/total | F6–K9 | Per cent with excess | Reference              |
|--------------|-----------|--------------|-------|----------------------|--------------|-------|----------------------|------------------------|
| λ Orionis    | 5 ± 1     | 16/44        | 36$^{+9}_{-6}$ | 22/401               | 5$^{+90}_{-4}$ | –     | –                   | Hernández et al. (2009, 2010) |
| Orion OB1    | 5 ± 1     | 11/28        | 39$^{+12}_{-16}$ | 3/5X                 | –           | –     | –                   | Hernández et al. (2006)       |
| Upper Sco    | 5 ± 1     | 10/70        | 14$^{+6}_{-4}$   | 6/23                 | 26$^{+16}_{-10}$ | –     | 12/29                | Carpenter et al. (2009); Chen et al. (2005a) |
| Orion OB1a   | 8.5 ± 1.5 | 12/25        | 56$^{+19}_{-15}$ | 1/1X                 | –           | –     | 2/12                 | Hernández et al. (2006)       |
| β Pictoris   | 12 ± 6    | 5/9X         | –       | 2/12                 | 17$^{+19}_{-11}$ | –     | 14/22                | Rebull et al. (2008)          |
| Sco–Cen      | 13 ± 25   | 32/19        | 52$^{+14}_{-19}$ | 3/11                 | 27$^{+15}_{-15}$ | –     | 1/10                 | Chen et al. (2005a)           |
| NGC 1960     | 16$^{+10}_{-5}$ | 21/71      | 30$^{+24}_{-7}$ | 14/61                | 23$^{+69}_{-9}$ | –     | 3/5                  | This paper                      |
| NGC 2232     | 25 ± 4    | 9/23         | 39$^{+26}_{-13}$ | 4/15                 | 26$^{+13}_{-13}$ | –     | 2/3                  | Currie et al. (2008b)            |
| IC 4665      | 27 ± 5    | 9/23         | 39$^{+13}_{-13}$ | 12/29                | 41$^{+16}_{-12}$ | –     | 2/1                  | Smith et al. (2011)             |
| NGC 2547     | 35 ± 5    | 15/33        | 45$^{+15}_{-12}$ | 21/41                | 51$^{+14}_{-13}$ | –     | 2/3                  | Gorlova et al. (2007)           |
| IC 2391      | 50 ± 5    | 2/18         | 11$^{+5}_{-15}$  | 6/13                 | 46$^{+28}_{-18}$ | –     | 2/4                  | Siegler et al. (2007)           |
| Blanco 1     | 100 ± 20  | 4/12         | 33$^{+26}_{-16}$ | 1/25                 | 4$^{+9}_{-5}$  | –     | 2/7                  | Stauffer et al. (2010)          |
| The Pleiades | 115 ± 20  | 7/44         | 16$^{+9}_{-10}$  | 3/38                 | 13$^{+8}_{-6}$ | –     | 1/1                  | Gorlova et al. (2006)           |
| The Hyades   | 625 ± 50  | 1/11         | 9$^{+2}_{-1}$    | 1/67                 | 1$^{+3}_{-1}$  | –     | 1/1                  | Cieza et al. (2009)            |
| Field        | 4000$^a$  | 0/4X         | –       | 6/65                 | 9$^{+8}_{-6}$  | –     | 2/4                  | Bryden et al. (2006)            |

$^a$Frequency of excess emission in this spectral range is highly uncertain due to the low number of stars, and so this point is omitted from Fig. 7 or 9.

$^b$Average age for all stars in this paper.
we include observed excess emission from stars in h and \( \chi \) Persei (Currie et al. 2008a) which were excluded from the statistical analysis because of uncertain membership lists, and \( \beta \) Pictoris and the field stars which were excluded from Fig. 7 because of the low number of objects (see Table 5). Here, we again see that NGC 1960 (shown by the diamonds) is comparable to other clusters of similar age. Bright star 14, which has the highest levels of excess emission in this cluster (and also has excess in the near-infrared), has one of the highest levels of excess emission observed, although its SED shows that the emission is consistent with debris disc emission rather than that from a primordial disc (see Section 4). This figure displays more clearly that there is a ‘rise and fall’ in the upper envelope of 24 \( \mu \)m excess emission, as the peak levels of 24 \( \mu \)m excess reach a maximum at \( \sim 10–20 \) Myr before falling off. A fall-off proportional to time is expected from models of the evolution of debris discs (e.g. Dominik & Decin 2003; Wyatt et al. 2007).

We show the same plots for lower mass stars of spectral types F6–K9. In Fig. 9, we can see that the frequency of 24 \( \mu \)m excess falls off roughly in proportion to time after \( \sim 50 \) Myr. NGC 1960 has a fairly typical excess frequency for its age (23\(^{+69}_{-9}\)% per cent), although given the large upper limit, we have really defined a lower limit to the frequency of >23 per cent (excluding the Poisson statistical errors). There is some evidence of the ‘rise and fall’ of debris discs seen in higher mass stars, although again the statistics for the younger clusters are highly uncertain. In this plot, it appears that the peak frequencies of debris discs around F6–K9 type stars are seen in clusters of ages \( \sim 30–50 \) Myr with an abrupt fall-off at \( \sim 100 \) Myr (see also Table 5). This is slower than the expected time taken to form Pluto-mass protoplanets at \( \sim 1 \) au, and in fact according to the models of Kenyon & Bromley (2005), a later peak in the 24 \( \mu \)m excess emission is to be expected for discs at greater distances from the star (see figs 7 and 8 of Kenyon & Bromley 2005). This suggests that rather than witnessing excesses arising from terrestrial planet regions around F6–K9 type stars, we may be seeing the inner edge of more distant planetesimal belts (due to the apparently smooth increase in frequencies towards a peak at 30–50 Myr). Constraints on longer wavelength emission for the cluster samples would be required to explore this possibility. Siegler et al. (2007) found evidence that for clusters older than 10 Myr the frequency of 24 \( \mu \)m excess emission fell off steadily. We do not find such a strong relation in our data (we have considered a larger set of cluster samples), although it is clear that by 100 Myr excess frequencies are very low. These differences are likely to arise from different criteria for identifying the presence of excess. This plot demonstrates that the frequency of debris disc emission is likely

\[ [24]_{\text{obs}} - [24]_{\text{pred}} \]

**Figure 8.** The 24 \( \mu \)m excess emission of stars of spectral types B0–F5 as a function of age. Clusters are listed in the text. Data for NGC 1960 are shown by the diamonds and offset in age to 18 Myr to avoid confusion with the Sco–Cen association. The grey symbols mark 3\( \sigma \) upper limits for sources with low signal-to-noise-ratio 24-\( \mu \)m data.

**Figure 9.** The frequency of 24 \( \mu \)m excess emission of stars of spectral types F6–K9 as a function of age. Clusters are listed in the text and in Table 5. The datum for NGC 1960 is shown by the diamond and offset in age to 18 Myr to avoid confusion with the Sco–Cen association.
Debris discs in NGC 1960

Figure 10. The 24 μm excess emission of stars of spectral types F6–K9 as a function of age. Clusters are listed in the text. Data for NGC 1960 are shown by the diamonds and offset in age to 18 Myr to avoid confusion with the Sco–Cen association. The grey symbols mark 3σ upper limits for sources with low-signal-to-noise-ratio 24-μm data.

to be a function of many factors aside from the age of the cluster; however, with the small numbers of clusters under consideration, an examination of these factors is beyond the scope of this paper.

In Fig. 10, we see that the levels of excess emission observed around stars in the spectral range F6–K9 in NGC 1960 are typical for stars of similar age. We do not see evidence for a delayed peak (levels of excess emission being higher in clusters ∼10–20 Myr old) in this spectral range. This may in part be due to residual primordial disc populations at 5 Myr around lower mass stars, for example, those seen in Upper Scorpius (sources in this cluster with [24]_pred − [24]_obs > 4 were determined to be primordial in Carpenter et al. 2009). However, removal of the primordial disc targets would mean that the frequency of true debris discs in these clusters is lower, and therefore the evidence for a delayed peak would be stronger. In common with the drop-off in frequency of excess in this spectral range, high levels of excess emission are not seen at ages ≥100 Myr in these clusters.

Interestingly, for NGC 1960 we see no evidence that either the frequency or the levels of excess emission at 24 μm are dependent on spectral type. This is somewhat contrary to the expectation that 24 μm excess should be longer lived around brighter stars, which arises from the difference in time taken to form planetesimals at larger radial distances around A-type stars (excess detected at ≥24 μm implies a temperature of 100–150 K, translating into an offset of 3–30 au around A- and early-F-type stars, and 0.5–3 au around solar-type stars assuming thermal equilibrium). Within the context of current planet formation theories (Kenyon & Bromley 2005, 2006), we might expect the 24 μm emission around lower mass stars of ∼16 Myr to be the result of massive collisions between protoplanetary bodies, and we might expect it to occur less frequently than the planetesimal collisions thought to be responsible for the 24 μm emission around higher mass stars. In fact, for the majority of the clusters listed in Table 5, there is no significant difference between the frequency of excess emission observed around B0–F5 type stars and that observed around F6–K9 type stars. However, for the majority of clusters older than >5 Myr, the typical levels of excess emission observed around higher mass stars are higher than that observed around lower mass stars (see Figs 8 and 10), which does agree with the model predictions. This does not appear to be the case for NGC 1960. The highest observed excess is indeed observed around a higher mass star (bright target 14), but in general the levels of excess emission observed are similar, regardless of the V − K_S colour (proxy for spectral type). Our results are biased by the fact that only relatively high levels of excess will be detected around lower mass stars, and so there is probably a population of stars in the range F6–K9 with lower levels of excess than shown in Fig. 10. However, as we do not see a population of higher mass stars with larger excesses (excluding bright star 14), these results might suggest that there are a large number of lower mass sources in the NGC 1960 cluster that are currently undergoing massive collisions. The reason why many sources in the cluster should experience massive collisions at a similar time is unclear, and if this is the reason for the 24 μm excess observed around lower mass stars, this presents a challenge to current planet formation theories. In Table 6, we show the frequencies of stars with large 24 μm excess ([24]_pred − [24]_obs > 2) for clusters with populations >10 stars in both spectral bins. From these statistics, we cannot see a significant difference between the frequencies of large excess emission observed in NGC 1960 and other clusters. We do find some evidence that the frequency of stars with large excess emission drops at ≥25 Myr amongst both high- and low-mass samples, which is in agreement with steady-state evolution models.
cannot determine if the relationship between the frequency of large excesses in the lower mass (F6–K9 type) and higher mass (B0–F5 type) spectral bins is significantly different for NGC 1960, partly due to the high errors involved (errors on the frequencies were determined in the same way as errors on the overall excess frequencies in Table 5). With the current data, we have no statistically significant evidence that NGC 1960 is different from other clusters of similar age.

In summary, the levels and frequency of excess emission seen in NGC 1960 are not significantly different from those of other open clusters of similar age. Bright target 14 (BD +34°1098) has one of the highest levels of excess emission observed in early-type stars, but SED fitting has shown that this is consistent with debris as opposed to primordial emission.

5.2.2 Excess emission at 8 \( \mu \)m

A subset of the open clusters discussed above also have published 8-\( \mu \)m IRAC photometry. We consider how the frequency of 8-\( \mu \)m excess evolves with time. Frequencies are listed by age and spectral bin in Table 7. Errors on frequency are derived from upper limits and the Poisson statistics of Gehrels (1986) as described for the 24-\( \mu \)m data in the preceding section.

Table 6. The frequencies of large excess emission ([24]_{\text{pred}} – [24]_{\text{obs}} > 2) among open clusters with published 24-\( \mu \)m MIPS photometry.

| Name           | Age (Myr) | Excess/total | B0–F5 Per cent with excess | Excess/total | F6–K9 Per cent with excess | Reference                  |
|----------------|-----------|--------------|-----------------------------|--------------|---------------------------|----------------------------|
| λ Orionis      | 5 ± 1     | 0/44         | 0.6^4                      | 4/401        | 1.1^4                     | Hernández et al. (2009, 2010) |
| Upper Sco      | 5 ± 1     | 2/70         | 3.7^4                      | 6/23         | 26.1^16                   | Carpenter et al. (2009); Chen et al. (2005a) |
| Sco–Cen        | 16–17     | 5/25         | 20.13^4                    | 1/11         | 9.1^21                    | Chen et al. (2005a)         |
| NGC 1960       | 16.10^5   | 3/71         | 4.1^4                      | 8/61         | 13.6^6                    | This paper                 |
| NGC 2232       | 25 ± 4    | 1/23         | 4.1^4                      | 0/15         | 0.12^4                    | Currie et al. (2008b)       |
| IC 4665        | 27 ± 5    | 0/23         | 0.1^1                      | 0/29         | 0.6^4                     | Smith et al. (2011)         |
| NGC 2547       | 35 ± 5    | 0/33         | 0.1^1                      | 2/41         | 5.9^3                     | Gorlova et al. (2007)       |
| IC 2391        | 50 ± 5    | 0/18         | 0.1^1                      | 0/13         | 0.14^4                    | Siegler et al. (2007)       |
| Blanco 1       | 100 ± 20  | 0/12         | 0.1^1                      | 0/25         | 0.7^3                     | Stauffer et al. (2010)      |
| The Pleiades   | 115 ± 20  | 0/44         | 0.1^1                      | 0/38         | 0.5^5                     | Gorlova et al. (2006)       |
| The Hyades     | 625 ± 50  | 0/11         | 0.1^1                      | 0/67         | 0.6^3                     | Cieza et al. (2009)         |

Notes. Errors on excess frequencies are determined in the same manner as for Table 5 (as described in the text). Only clusters with 24-\( \mu \)m observations of >10 stars in each spectral bin have been included in this table.

These figures confirm that 8-\( \mu \)m excess emission is rare amongst stars with age \( \geq 5 \) Myr. We do not see any evidence for a dependence of 8-\( \mu \)m excess frequency on the age of the cluster. As we only have upper limits for many of the clusters, particularly for the lower mass spectral bin, any dependence of 8-\( \mu \)m frequency on age or spectral type is difficult to determine. However, we can state that the 8-\( \mu \)m excess frequency is always lower than the 24-\( \mu \)m frequency.

6 CONCLUSIONS

In this paper, we have presented a study of the cluster NGC 1960 (M36) using archival Spitzer MIPS and IRAC data. These data have been used to search for debris discs in the cluster. Our conclusions are as follows:

(i) We have identified 38 targets as having significant 24-\( \mu \)m excess. One target, bright star 14 (BD +34°1098), has very high levels of excess (\( F_{24}/F_{\text{IRAC}} \sim 85 \)). Three targets (including BD +34°1098) have significant excess emission at near-infrared wavelengths. The excess evolves with time. Frequencies are listed by age and spectral bin as opposed to primordial emission.

Table 7. The excess frequencies of open clusters with published 8-\( \mu \)m IRAC photometry.

| Name           | Age (Myr) | Excess/total | B0–F5 Per cent with excess | Excess/total | F6–K9 Per cent with excess | Reference                  |
|----------------|-----------|--------------|-----------------------------|--------------|---------------------------|----------------------------|
| λ Orionis      | 5 ± 1     | 2/44         | 5.6^4                       | 15/401       | 4.1^4                     | Hernández et al. (2009, 2010) |
| Orion OB1b     | 5 ± 1     | 1/29         | 3.3^4                       | 0/5^2        | –                         | Hernández et al. (2006)     |
| Upper Sco      | 5 ± 1     | 5/68         | 7.5^3                       | 4/45         | 9.5^3                     | Carpenter et al. (2006)     |
| Orion OB1a     | 8.5 ± 1.5 | 2/25         | 8.12^4                      | 0/1^X        | –                         | Hernández et al. (2006)     |
| NGC 1960       | 16.10^5   | 3/71         | 4.1^4                       | 0/61         | <7                        | This paper                 |
| NGC 2232       | 25 ± 4    | 1/23         | 4.1^4                       | 1/15         | 7.15^6                    | Currie et al. (2008b)       |
| IC 4665        | 27 ± 5    | 1/23         | 4.1^4                       | 0/29         | <10                       | Smith et al. (2011)         |
| NGC 2547       | 35 ± 5    | 2/33         | 6.5^2                       | 2/41         | 5.1^3                     | Gorlova et al. (2007)       |

^3Frequency of excess emission in this spectral range highly uncertain due to the low number of stars.
SEDs of these targets have been examined and the emission has been determined to be consistent with second-generation debris emission, as opposed to remnant primordial discs.

(ii) The frequency and overall levels of excess emission observed in NGC 1960 are consistent with other clusters of similar age (> 30 per cent of B0–F5 type stars and > 23 per cent of F6–K9 stars have significant excess). The data from this cluster are consistent with a ‘rise and fall’ in debris disc emission amongst higher mass stars, and with a possible delayed peak in emission amongst lower mass stars.

(iii) We find no evidence for a dependence of excess emission on stellar multiplicity. We are, however, restricted in our examination of this relationship by a lack of completeness in the 24-μm-flux measurements for intermediate to lower mass stars.

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**SUPPORTING INFORMATION**

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

**Table 1.** Target sources in NGC 1960 from Sanner et al. (2000).
**Table 2.** The lower mass target sources in NGC 1960.
**Table 3.** *Spitzer* IRAC and MIPS 24-µm photometry for bright members of NGC 1960.
**Table 4.** *Spitzer* IRAC and MIPS 24-µm photometry for low-mass members of NGC 1960.

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