Searching for debris discs in the 30 Myr open cluster IC 4665*

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ABSTRACT

Context. Debris discs orbiting young stars are key to understanding dust evolution and the planetary formation process. We take advantage of a recent membership analysis of the 30 Myr nearby open cluster IC 4665 based on the Gaia and DANCe surveys to revisit the disc population of this cluster.

Aims. We aim to study the disc population of IC 4665 using Spitzer (MIPS and IRAC) and WISE photometry.

Methods. We use several colour–colour diagrams with empirical photospheric sequences to detect the sources with an infrared excess. Independently, we also fit the spectral energy distribution (SED) of our debris-disc candidates with the Virtual Observatory SED analyser (VOSA) which is capable of automatically detecting infrared excesses and provides effective temperature estimates.

Results. We find six candidate debris-disc host stars (five with MIPS and one with WISE), two of which are new candidates. We estimate a disc fraction of 24 ± 10% for the B–A stars, where our sample is expected to be complete. This is similar to what has been reported in other clusters of similar ages (Upper Centaurus Lupus, Lower Centaurus Crux, the β Pictoris moving group, and the Pleiades). For solar-type stars we find a disc fraction of 9 ± 9%, which is lower than that observed in regions with comparable ages.

Conclusions. Our candidate debris-disc host stars are excellent targets to be studied with ALMA or the future James Webb Space Telescope (JWST).

Key words. circumstellar matter – infrared: stars – open clusters and associations: individual: IC 4665

1. Introduction

Debris discs are the result of collisions between planetesimals and their detection therefore implies that the planet formation process was successful in forming bodies of a few hundred or a few thousand kilometres (see e.g. Hughes et al. 2018, for a recent review on debris discs). Stars hosting debris discs are excellent places to image planets and discs simultaneously; see for example Fomalhaut (Kalas et al. 2008), β Pictoris (Lagrange et al. 2010), HR8799 (Marois et al. 2008). This is because they are optically thin in the infrared (IR), and planets can be imaged because they offer the best contrast with respect to the star. On the contrary, protoplanetary discs are optically thick at these wavelengths, hindering the observation of planets. In addition, the study of debris discs can provide clues as to the composition of exoplanets as well as their orbits and masses (e.g. Hughes et al. 2018).

The first debris disc was discovered around Vega using the Infrared Astronomical Satellite (IRAS) by Aumann et al. (1984). Since then, several studies have been devoted to searching for debris discs in the solar vicinity (e.g. Moór et al. 2006; Rhee et al. 2007; Zuckerman et al. 2011). One of the main questions addressed by these studies is the temporal evolution of debris discs, the elucidation of which is only possible if accurate age measurements are available, which is in general not common for isolated stars. The easiest way to tackle this issue is to study debris discs hosted by stars members of a known association or open cluster where the age estimates are much more reliable. In the past decade, a number of studies reported the frequency of IR excesses in clusters of different ages (e.g. Gorlova et al. 2006, 2007; Siegler et al. 2007). These joint efforts complemented by others on field stars suggested a debris disc fraction decay inversely proportional to the age (Rieke et al. 2005).

IC 4665 is among the sample of young open clusters examined in the literature to search for debris discs. This is a young open cluster with an estimated age of 27.7 ± 2.5 Myr (Manzi et al. 2008) and an average distance of 350 pc (Miret-Roig et al. 2019). Several works have studied the cluster population (Hogg & Kron 1955; Prosser & Giampapa 1994; de Wit et al. 2006; Jeffries et al. 2009; Lodieu et al. 2011). Recently, Miret-Roig et al. (2019) updated the cluster census using photometric and astrometric information, providing a list of more than 800 highly probable cluster members. Smith et al. (2011) searched for debris discs in IC 4665 based on Spitzer observations. These latter authors started from a sample of 75 members and obtained a disc fraction of 27±9%. The authors also reported a disc fraction for solar-type stars (F5–K5) of 42±18% which they claimed to be higher than what had been found in other clusters of similar ages, although compatible within the uncertainties (e.g. Gorlova et al. 2007 found a F0–F9 fraction of 33±13% for the 30 Myr NGC 2547 open cluster).

In this work, we take advantage of the recent census by Miret-Roig et al. (2019) to revisit the study of debris discs in this cluster. In Sect. 2 we describe our sample and dataset which combines photometry from DANCe, WISE, and Spitzer. In Sect. 3 we present our empirical method to detect IR excesses with colour–colour diagrams. In Sect. 4 we confirm...
our candidates by comparing their spectral energy distribution (SED) to models of photospheric emission. In Sect. 5 we discuss the candidates individually, and in Sect. 6 we compute the disc fraction and compare it to other studies. Finally, in Sect. 7 we present our conclusions.

2. Data

We start from a list of 819 candidate members of IC 4665 (Miret-Roig et al. 2019) covering a magnitude range of 12.4 mag ($7 < J < 19.4$ mag). This sample was selected by combining photometry and astrometry from the Gaia Data Release 2 (DR2, Gaia Collaboration 2016, 2018) and the ground-based survey DANCe (Dynamical Analysis of Nearby Clusters, Bouy et al. 2013) in a Bayesian membership algorithm. The resulting sample is expected to be significantly more complete and reliable than the one previously used by Smith et al. (2011) to study debris discs in this cluster. Their sample contained 40 spectroscopic low-mass members from Jeffries et al. (2009), 33 brighter stars selected with proper motions and B, V photometry from the Tycho-2 catalogue (Hog et al. 2000), and two additional members from Prosser & Giampapa (1994). The recent Gaia DR2 astrometry allows us to discard 24 of their 75 targets (32%) as non-members at a high level of confidence, hence motivating a re-analysis of the cluster disc frequency.

2.1. Photometric database

We used all the optical and IR photometry available in the DANCe catalogue\(^1\), i.e., $G, G_{BP}, G_{RP}, g, r, i, z, y, J, H, K_s$. We also cross-matched (using a cross-match radius of 1\(''\)) our sample with the AllWISE catalogue (Wright et al. 2010) and found 704 sources with a counterpart in the W1 (3.4\,$\mu$m), W2 (4.6\,$\mu$m), W3 (12.1\,$\mu$m), and W4 (22.2\,$\mu$m) bands.

We queried the Spitzer Heritage Archive for all the IRAC1 (4.6\,$\mu$m), IRAC2 (4.5\,$\mu$m), IRAC3 (5.8\,$\mu$m), IRAC4 (8.0\,$\mu$m), and MIPS1 (24\,$\mu$m) data within a radius of 3\(''\) (the estimated size of the cluster) around the centre. The program IDs of the observations in this area are given in Table 1 and the footprints of the various bands are displayed in Fig. 1. The majority of the data come from program ID 40601 which was analysed by Smith et al. (2011), but a significant number of images were added from program ID 3347 over part of the area. Our reduction began from the S18.25.0 pipeline-processed artifact Corrected Basic Calibrated Data (CBCD) in the case of IRAC, and from the S18.12.0 pipeline-processed Basic Calibrated Data (BCDs) in the case of MIPS. The self-calibration recommended in the Spitzer Data Analysis Cookbook was applied in the case of MIPS to remove artefacts as well as bright and dark latents present in the BCD images. We then combined these into deep mosaics using the recommended version 18 of MOPEX (MOsaicker and Point source EXtractor) provided by the Spitzer Science Center using the standard parameters (see the MOPEX User’s Guide for details on the data reduction).

In the case of IRAC, point sources were detected using SExtractor (Bertin & Arnouts 1996), and their PRF-fitting photometry was measured using APEX, the photometry package that is part of MOPEX. According to the manual, the colour corrections tabulated in the IRAC and MIPS handbooks are marginal for our sources ($T_{\text{eff}} > 4000$ K) and we therefore neglected them.

In the case of MIPS, an extra step was performed before extracting the sources and measuring their photometry. The presence of a bright extended nebulousity (see Fig. 2) indeed compromises the detection and measurements as the background estimations implemented in SExtractor and APEX are not optimised to deal with such extended emission. We therefore applied the nebulousity filter described in Irwin (2010) to the pipeline-produced mosaic. A spatially variable point spread function (PSF) was then computed using PSFEx (Bertin 2013) and the final PSF photometry was extracted using SExtractor again. We verified that the SExtractor PSF and APEX fluxes were in good agreement within the uncertainties, but kept SExtractor measurements as it detected and deblended more sources than APEX. To calibrate the fluxes of SExtractor we used the APEX photometry as reference and computed a linear fit which resulted in a zero point of $140.89 \pm 0.12$ Jy. We applied this zero point to all the SExtractor fluxes, and its uncertainty was added quadratically to the flux error. To convert fluxes into magnitudes we used the magnitude zero points provided in the instruments handbooks; for IRAC these are 280.9 Jy, 179.7 Jy, 115.0 Jy, and 64.9 Jy for bands 1, 2, 3, and 4, respectively, and for MIPS1 this is 7.17 Jy. As explained in the instruments handbooks, the estimated level of accuracy of the photometric measurements is of 3% for IRAC and 4% for MIPS1. Therefore, we also added these uncertainties in quadrature to the statistical flux uncertainties. We estimated the global offset of our sources with respect to Gaia DR2 and

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\(^1\) http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/A+A/631/A57
Photometric measurements can be affected by a number of problems (e.g. saturation, blending with a nearby source, cosmic rays, etc.) which can alter the true values and lead to unreliable measurements. Such contaminated photometric measurements can lead to a false IR excess detection or prevent the detection of a real excess. To minimise the impact of dubious photometric measurements, we applied filtering criteria specifically designed for each instrument.

### 2.2. Photometry filtering

Photometric measurements can be affected by a number of problems (e.g. saturation, blending with a nearby source, cosmic rays, etc.) which can alter the true values and lead to unreliable measurements. Such contaminated photometric measurements can lead to a false IR excess detection or prevent the detection of a real excess. To minimise the impact of dubious photometric measurements, we applied filtering criteria specifically designed for each instrument.

The WISE photometry is widely known to be affected by a large number of artefacts which are identified and flagged in the AllWISE catalogue. Filtering these sources is essential to discarding unreliable photometry. In this work we applied the following filtering:

- “cc_flags”. We only keep sources with 0 flag, which means that they are unaffected by any of the known artefacts.
- “ext_flg”. We only keep sources with 0 flag, which means that they are point-source objects, excluding extended objects.
- “ph_qual” is the photometric quality flag. We consider flags A (signal-to-noise ratio, $S/N \geq 10$) and B ($3 < S/N < 10$) as good-quality photometry, flags C ($2 < S/N < 3$) as poor-quality photometry, and flag U ($S/N < 2$) as an upper limit. The poor-quality photometry and the upper limits are not included in the photometric measurements.

### Table 2. Number and percentage of members of IC 4665 detected for each photometric band before and after filtering the photometry.

| Filter | Initial | Num. | Pct. | After filtering | Num. | Pct. |
|--------|---------|------|------|-----------------|------|------|
| $G$    |         | 766  | 94%  | 766             | 94%  |
| $G_{HP}$ |       | 698  | 85%  | 698             | 85%  |
| $G_{RP}$ |       | 699  | 85%  | 699             | 85%  |
| $g$    |         | 766  | 94%  | 766             | 94%  |
| $r$    |         | 695  | 85%  | 695             | 85%  |
| $i$    |         | 766  | 94%  | 766             | 94%  |
| $z$    |         | 755  | 92%  | 755             | 92%  |
| $y$    |         | 789  | 96%  | 789             | 96%  |
| $J$    |         | 815  | 100% | 815             | 100% |
| $H$    |         | 781  | 95%  | 781             | 95%  |
| $K$    |         | 778  | 95%  | 778             | 95%  |
| $W1$   |         | 704  | 86%  | 577             | 70%  |
| $W2$   |         | 704  | 86%  | 560             | 68%  |
| $W3$   |         | 704  | 86%  | 148             | 18%  |
| $W4$   |         | 704  | 86%  | 18              | 2%   |
| IRAC1  |         | 218  | 27%  | 218             | 27%  |
| IRAC2  |         | 219  | 27%  | 219             | 27%  |
| IRAC3  |         | 204  | 25%  | 202             | 25%  |
| IRAC4  |         | 200  | 24%  | 199             | 24%  |
| MIPS1  |         | 45   | 5%   | 45              | 5%   |

**Notes.** The total number of members is 819.
Fig. 3. Top: comparison between the MIPS1 photometry obtained in this work and that published on Smith et al. (2011) for the common sources. Bottom: Spatial distribution of the sources with excess in this work (red dots, labelled as follows, A: 2MASS J17462472+0517213, B: HD 161733, C: HD 161621, D: TYC 428-1938-1, E: TYC 428-980-1, F: HD 161734) and in Smith et al. (2011) (blue squares). The areas limited by green lines indicate the coverage of the Spitzer program ID 3347 which was not included in Smith et al. (2011).

shown throughout our analysis but are not considered as reliable measurements.

For Spitzer observations, we discarded any detection with $S/N < 3$. Detections with $3 < S/N < 5$ are considered to be marginal and they should be considered with caution. In Table 2 we report the number of sources detected in each band before and after the filtering process. In spite of their better sensitivity, the Spitzer images include less sources simply because they cover a smaller area ($1 \times 1^\circ$, see Fig. 1). Another important remark is that WISE detections are the most affected by our filtering criteria, especially at longer wavelengths (W3 and W4) where many sources are only detected as upper limits. In Fig. 4 we see the magnitude distribution of the members of IC 4665 in the mid-infrared (MIR) photometric bands. There are 45 sources with MIPS1 photometry in the magnitude range 7.2–12.4 mag. The detection limit of the W4 channel at 22 $\mu$m is slightly shallower and there are 18 sources in the magnitude range between 7 and 8.6 mag.

2.3. Completeness

One of the goals of this study is to measure the debris disc fraction of IC 4665. For that, defining a sample for which the photometric surveys are complete is crucial to interpreting the results and comparing with other studies. Establishing the completeness of photometric surveys can be a complex task, especially when variable extended emission is present (see Fig. 2).

In the following, we derive an estimate of the completeness limits of the photometric filters MIPS1 and W4. We take the maximum of the magnitude distribution of all the sources in the field of view (members and field stars) as the completeness limit. These distributions show a maximum around 11.8 mag for MIPS1 and around 8.5 mag for W4. We find no significant variations in the areas affected by the extended emission and, as a first approximation, use these numbers for the entire survey. To convert the completeness in magnitude to a fundamental parameter such as the mass, we used the BT-Settl atmospheric models of Allard (2014). At the age and distance of IC 4665, we find that the magnitude limit of MIPS1 corresponds to a temperature of 4000 K and a mass of 0.75 $M_\odot$. This corresponds to a spectral type of mid-K (Table A.5 from Kenyon & Hartmann 1995). The BT-Settl models do not cover the hottest objects and cannot be used to convert the W4 completeness limit in magnitude.
In order to identify cluster members with debris discs, we use the mass of 1.75 \( M_{\odot} \) empirical relation defined by the members of IC 4665. The location of this mass is indicated by the solid line and the 3\( \sigma \) uncertainties of IC 4665 with 24\( \mu \)m data. This is shown in Fig. 5.

The photometric colour \( K_s - [24] \) is commonly used in the literature to detect sources with IR excess, it is essential to follow a different approach and transformed the W4 magnitude to a \( G - K_s \) colour using an empirical relation defined by the members of IC 4665. The limiting magnitude of W4 = 8.5 mag corresponds to an intrinsic \( G - K_s \approx 0.2 \) mag (assuming an extinction \( A_V = 0.46 \) mag). This colour corresponds to an effective temperature of 8400 K and a mass of 1.75 \( M_{\odot} \), according to the PARSEC-COLIBRI models (Marigo et al. 2017). This is equivalent to a spectral type of mid-A (Kenyon & Hartmann 1995).

3. Infrared excess detection

In order to identify cluster members with debris discs, we use colour–colour diagrams to detect IR excesses at different wavelengths, a method that is entirely empirical. We chose to analyse the WISE and Spitzer data independently because of their significantly different wavelength coverage, spatial resolution, and sensitivities.

3.1. MIPS 24\( \mu \)m data

The photometric colour \( K_s - [24] \) is commonly used in the literature to detect sources with 24\( \mu \)m excess emission (e.g. Gorlova et al. 2006; Stauffer et al. 2010). We followed the methodology of these works and used colour–colour diagrams to discern between the excess and non-excess population. The only difference is that we used the photometry of the recent Gaia DR2 G filter which is more precise, uniform, and extended than the Johnson V filter.

In order to detect sources with IR excess, it is essential to first outline the location of the sources with photospheric colours (i.e. those which do not have an IR excess). We used the Spitzer observations in the Pleiades of Gorlova et al. (2006) to define the photospheric sequence in the \( (G - K_s) - (K_s - [24]) \) colour–colour diagram. We note that this is the same approach that Gorlova et al. (2007) used for the 30–40 Myr cluster NGC 2547. Indeed, several authors have found similar relations in young clusters (e.g. Stauffer et al. 2010 for the Hyades, and Plavchan et al. 2009 for nearby young stars). We used only the reliable 24\( \mu \)m photometry for the Pleiades sources classified as not having excess by the authors\(^2\). Equivalently to what they did, we fitted a linear polynomial relation (see Fig. A.1) and obtained:

\[
(K_s - [24]) = 0.102(\pm 0.013) \times (G - K_s) - 0.12(\pm 0.02). \tag{1}
\]

We used this relation to define the photospheric emission locus in our data. To establish a confidence interval in which we believe that there is no emission excess, we fitted a segmented linear function with two slopes to account for the fact that at high S/N the measurements are dominated by photon noise and at low S/N by Poisson noise (see Fig. A.2). The point of change in trend is a free parameter of the fitting process.

\[
e_{[24]} = \begin{cases} 
    c_1 + k_1 \times (G - K_s), & (G - K_s) < 1.34 \\
    c_2 + k_2 \times (G - K_s), & (G - K_s) \geq 1.34.
\end{cases} \tag{2}
\]

The parameters of the fit are \( c_1 = 0.042(\pm 0.018) \) mag, \( c_2 = -0.07(\pm 0.05) \) mag, \( k_1 = 0.008(\pm 0.011) \), and \( k_2 = 0.09(\pm 0.03) \). We consider that sources with a colour \( K_s - [24] \) larger (within the uncertainties) than the photospheric emission locus plus the 3\( \sigma \) uncertainties of the 24\( \mu \)m photometry have an excess in the 24\( \mu \)m emission. According to this criterion, we find 5/45 candidates with excesses in the 24\( \mu \)m emission. Three (HD 161733, TYC 428-1938-1, and 2MASS J17462472+0517213) had already been reported by Smith et al. (2011) and the other two (HD 161621 and TYC 428-980-1) are new candidates. In Fig. 6 we see that all the candidates have a clear detection in all the Spitzer photometric bands.

Smith et al. (2011) detected 14 additional sources with 24\( \mu \)m excesses not present in our analysis. Four of them are simply not classified as members by Miret-Roig et al. (2019) and therefore were not considered in this study. We confirmed that three out of these four do not show any excess at 24\( \mu \)m according to our photometry. The fourth object (HD 161734) has WISE+Spitzer excesses in our photometry (see Figs. 5, 7, and 8) but it had a low membership probability (\( p = 0.002\% \)) with Gaia in Miret-Roig et al. (2019) and therefore was not initially considered in this work. We refer to Sect. 5 for a more detailed discussion of this object. For the remaining ten sources, the MIPS 24\( \mu \)m photometry is significantly discrepant between the two studies (as shown in Fig. 3), which explains why they found an excess and we did not.

3.2. IRAC 3.6–8.0\( \mu \)m data

Similarly to what we did in Sect. 3.1 with the MIPS photometry, now we use the four channels of IRAC to search for possible candidates with a near-infrared (NIR) excess. In Fig. 7 we represent the colour–colour diagrams \( K_s - [3.6], K_s - [4.5], K_s - [5.8], K_s - [8.0] \) against \( G - K_s \). None of our members have an excess on any of the IRAC bands. There are a few points in each colour–colour diagram that seem to be much redder than the mean photospheric locus but none of them show an excess in two consecutive bands. These are spurious or blended detections in the images, or have a high \( \chi^2 \) of the PSF fit.

The source HD 161734 shows an increasing excess in the colour–colour diagrams of the IRAC channels. This excess was also detected by Smith et al. (2011) in the 5.8 and 8.0\( \mu \)m channels.
3.3. WISE 3.4–22.2\textmu m data

Similarly to what we did in Sect. 3.1 for MIPS and in Sect. 3.2 for IRAC, here we present colour–colour diagrams using the WISE photometry (see Fig. 8). The photometric measurements classified as “good” according to the criteria defined in Sect. 2.2 are represented by black dots. In these panels we have also represented data classified as “poor” to illustrate the loss of sensitivity at longer wavelengths, resulting in the overlap of good- and poor-quality data in W3 (mainly for the coldest objects) and W4 (almost along the whole cluster sequence). In the bands W1 (3.4\textmu m) and W2 (4.6\textmu m) we do not see any source with a significant excess, with the exceptions of TYC 428-980-1 which is flagged as a extended source by the WISE catalogue (probably due to the blending of nearby sources, see Fig. 9), and HD 161734 which shows an increasing excess in all the WISE bands.

In addition to HD 161734, in the W3 (12\textmu m) band we see two objects redder than the photospheric sequence defined by the majority of sources. One is HD 161261, a good candidate to host a debris disc since it also displays an excess in W4 (22\textmu m). Moreover, the WISE images of this source appear clean (see Fig. 9). We note that this source is not covered by Spitzer because is not in the central 1 \times 1 area. The second source is TYC 428-980-1, which, as mentioned above, was initially discarded because it was flagged as an extended object by the WISE catalogue. However, if we look at the WISE images (Fig. 9), we see that the source appears blended in the W1 and W2 bands, but not in W3 and W4, where the object shows an increasing excess. In Sect. 5 we discuss this object in detail, and explain
why the nearby source detected at shorter wavelengths might be unresolved in W3 and W4, with the subsequent contamination of the derived photometry.

As commented above, in bands W3 and W4 there is a significant increasing amount of poor-quality photometric measurements and upper limits. This is due to the limited sensitivity of WISE, and the increasing amount of diffuse emission present at those wavelengths.

There are a few sources at the limit of sensitivity which have not been flagged by WISE as poor and seem to have an excess. We checked the images and discarded them because they do not show any detected source.

4. Spectral energy distributions

We used the Spanish Virtual Observatory (SVO) tool VOSA\(^3\) (VO SED analyser, Bayo et al. 2008) to further investigate the sources that show significant excesses in the colour–colour diagrams. We use VOSA to fit their SED in order to (i) confirm whether or not the MIR excesses are automatically detected by the tool, and (ii) characterise the central sources in more detail.

We used all the photometry described in Sect. 2 excluding the filtered photometry, upper limits, and saturated measurements. In addition, we used the VOSA interface to search for the source with IR excess.

Bayesian distances inferred using Kalkayotl\(^4\) and the Gaia DR2 parallaxes. The resultant values are reported in Table 3. The extinction towards IC 4665 is not yet well constrained. The 3D dust map from Green et al. (2019) reports an extinction of \(A_V = 0.46^{+0.12}_{-0.06}\) mag at the position and distance of the cluster. Recently, Miret-Roig et al. (2019) estimated a median extinction of \(A_V = 0.72\) mag with the Gaia DR2 a_g_val and Anders et al. (2019) determined individual extinction values for our targets between 0.09 and 0.74 mag. As a consequence, we leave the extinction as a free parameter between 0 and 1 mag.

To find the model that best reproduces the observed SEDs, we used the option “Chi-square Fit”. This option calculates the synthetic photometry from theoretical spectra for the filters with observed data, and applies a statistical test to find the model that best reproduces the data. The fitting algorithm is able to detect possible IR excesses and then these points are no longer considered in the final fit. We used the theoretical atmospheres models of Kurucz (ODFNEW/NOVER models, Castelli et al. 1997) with solar metallicity. We allow VOSA to find the best \(\log g\) in the interval 4–5, and the best temperature in the range 5000 < \(T_{\text{eff}}\) < 20 000 K.

In Fig. 10, we present the observed SEDs together with the best-fit models, and in Table 3 we summarise some of their parameters. We see that VOSA independently finds an IR excess for six of the seven candidates for which an excess was detected in colour–colour diagrams (Sect. 3). The excess of HD 161733 is at the limit of the VOSA detection (\(\gtrsim 3\sigma\), see Sect. 5). In Table 3 we report the effective temperature measured with different techniques. The effective temperatures from Gaia DR2

\(^3\) http://svo2.cab.inta-csic.es/theory/vosa/

\(^4\) https://github.com/olivares-j/kalkayotl
(\(T_{\text{eff, GDR2}}\)) are computed from the three photometric bands of Gaia, and two colours which can be strongly correlated. In addition, these temperatures were obtained with a machine-learning algorithm only trained on the range 3000–10 000 K. Stars outside this range (which is the case for several of our candidates) can be systematically under- or overestimated (Andrae et al. 2018; Gaia Collaboration 2018). The effective temperatures from Smith et al. (2011) \(T_{\text{eff, S11}}\) are obtained from the \(B–V\) intrinsic colours through a relation provided by the authors. The differences between these two temperatures are a few hundred Kelvin, similar to what Andrae et al. (2018) found in the validation of the Gaia DR2 effective temperatures. Additionally, we provide the effective temperatures of the theoretical atmospheric model which best fits the observed SED \(T_{\text{eff, SED}}\). In all cases, the temperatures from the SED fitting have higher values with respect to the two photometric temperatures, particularly for the two hottest objects which have differences of thousands of Kelvins. In these cases, we have more confidence in the effective temperatures from our SED fitting because they rely on a larger amount of photometric measurements from different instruments (i.e. not correlated), covering a large fraction of the spectra (UV-IR), and are derived using the individual parallaxes for each object. Additionally, our effective temperatures better match the spectral types determined in the literature (see second column of Table 3).

5. Candidates of hosting a debris disc

We detected seven stars with MIR excesses in one or several of the Spitzer and WISE bands. In this section, we discuss them one by one.

5.1. HD 161261

HD 161261 displays excesses in W3 and W4 and the images show a clear detection in both cases. This source is not in the 1 x 1° central region of the cluster and thus is not covered by Spitzer. It is a new debris disc candidate. The effective temperature of the best theoretical atmospheric model is 12 000 K, significantly higher than the values obtained by Gaia DR2 and Smith et al. (2011). However, it matches well with the spectral class B9 from Cannon & Pickering (1993).

Interestingly, this source is classified as a rotating ellipsoidal variable by the General Catalogue of Variable Stars (Samus’ et al. 2017), which implies that it could be a close binary system. However, we find neither confirmation of the existence of this binary system nor any clues as to the properties of the possible companion.

5.2. HD 161733

HD 161733 shows a small excess in MIPS 24\(\mu\)m data (see Fig. 5). It is also detected in W4, but the uncertainties on the photometry are large, hindering confirmation of this excess with WISE. The best-fit SED corresponds to a model of \(T_{\text{eff}} = 15\ 000\) K, significantly hotter than the photometric temperatures of Gaia DR2 and Smith et al. (2011), but consistent with the strong helium lines present in its spectrum (e.g. Levato & Malaroda 1977; Hubrig & Mathys 1996), and the spectral classification found in the literature (e.g. Kraicheva et al. 1980; Cannon & Pickering 1993). The algorithm of VOSA did not detect an IR excess for this source when both W4 and MIPS1 are considered. We find that the MIPS 24\(\mu\)m observation shows a significance excess of 3.5\(\sigma\), at the limit of the algorithm.
Fig. 9. Multifilter WISE images of the IC 4665 sources with IR excesses.
**Table 3. Candidates for which we have detected an IR excess.**

| Object            | SpT (Ref.) | $G_{\text{eff}}$ | $A_v$ (mag) | $T_{\text{eff}}$ (K) | $\log g$ | $S_{\text{W}}$ (mag) | $S_{\text{24}}$ (mag) | Binary | New |
|-------------------|------------|------------------|-------------|----------------------|----------|----------------------|----------------------|--------|-----|
| HD 161261         | F9 V (1)   | 7705.35          | 3.41        | 6134.05              | 4.37     | 2.53                 | 4.49                 | N      |     |
| TYC 428-980-1 A   | A0 (3)     | 7750.00          | 4.00        | 6750.00              | 4.00     | 5.00                 | 5.00                 | N      | N   |
| 2MASS J17462472+0517213 | G2–G3 (4) | 5000.00          | 4.00        | 5000.00              | 4.00     | 5.00                 | 5.00                 | N      | N   |

**Notes.** Columns indicate: (1) object ID; (2) spectral type; (3) Bayesian distance; (4–5) Gaia DR2 and Smith et al. (2011); (6–7) photometric effective temperature and the 96% confidence level, $\log g$; (8–12) extinction, effective temperature and the 96% CL log $A_v$. The multiplicity of this source has been discussed in different works and the results are not conclusive. It was included in the catalogue of spectroscopic binaries of Kraicheva et al. (1980) based on radial-velocity studies (Abt et al. 1972; Pédoussaut & Carquillat 1973). However, the works of Crampton et al. (1976) and Morrell & Abt (1991) did not report any RV variability after the analysis of several spectra. According to the work of Kraicheva et al. (1980), the masses of the primary and the secondary are $4.3 M_\odot$ and $0.8 M_\odot$, respectively. This mass ratio cannot explain the excess we observe since the contribution of a $0.8 M_\odot$ star to the SED of a $4.3 M_\odot$ star is negligible. These authors also determined an orbital period of the system of $7.3 \pm 0.8$ days and a separation of $\sim 1.4$ AU. However, the nature of the spectroscopic binary is not confirmed and more observations are needed to characterise this source.

### 5.3. HD 161621

HD 161621 is a visual binary star with a separation of 3.2″ (Mason et al. 2001). The companion is the source TYC 428-1977-1. The two companions have very similar magnitudes ($G = 9.45$ mag; $G = 9.59$ mag), effective temperatures (7886 K; 7811 K), and parallaxes ($\sigma = 3.17 \pm 0.05$ mas; $\sigma = 3.29 \pm 0.04$ mas) indicating that it is an equal mass binary.

This system has a WISE counterpart at a separation of 1.6″ from the primary source. This is slightly larger than our initial search and so we added the WISE photometry manually. This source is flagged as an extended object by WISE and we verified that it is not resolved by this instrument. Moreover, this system is resolved by Gaia and IRAC, but is unresolved by the International Ultraviolet Explorer (IUE), WISE, and MIPS; 2MASS detects the two components but the photometry is flagged as contaminated.

We only used the photometry which resolved the system (Gaia and IRAC) to fit a SED (see Fig. A.3). We can see that all the unresolved channels (crosses) provided a photometric measurement systematically brighter than that predicted by the model. Our SED fit shows that the excess we detected with MIPS is due to the companion, because the excess is of 0.75 mag, exactly what we expect for an equal-mass binary. For this reason, we no longer consider this source as a candidate to host a debris disc.

### 5.4. TYC 428-1938-1

TYC 428-1938-1 displays an excess in 24 µm data which was already reported by Smith et al. (2011). This source has WISE photometry but the sensitivity of W3 is too low to be detected in that channel (see Fig. 9) and so we cannot use WISE to confirm this excess. The SED shows a 24 µm excess with respect to the photospheric emission.

### 5.5. TYC 428-980-1

TYC 428-980-1 displays excesses in W3, W4, and MIPS 24 µm. While the MIPS1 PSF fit shows a $\chi^2$ of 1.3, the source is flagged as an extended object in the WISE catalogue. Figures 6 and 9 show a close source at a separation of around 12″ but $\sim 100$ pc closer according to the Gaia DR2 parallaxes. Such a separation could be spatially resolved in the WISE W1 – W3 bands (not
in W4), and in MIPS 24 \( \mu \)m. The fact that this close source is detected neither in the W3 band nor in the MIPS1 image implies that the detected emission is associated to the central star. The SED of this object (see Fig. 10) shows that the detected emission is associated to the central star. We searched the WISE photometry finding an excess consistent with what is seen with IRAC and MIPS photometric reduction, we also detect an excess. Additionally, we searched the WISE photometry finding an excess consistent with what is seen with Spitzer (see Fig. 10). Smith et al. (2011) mention in their conclusions that this source may be a binary. However, they did not mention on what they based their hypothesis and we ourselves do not find any evidence of a binary nature. Based on its NIR excess, these latter authors also proposed that this source could have a remnant primordial disc. They were able to fit the excess with a 500 K blackbody, suggesting a dusty disc with a radius of 1.7 AU. Considering the members obtained with Gaia in Miret-Roig et al. (2019), the cluster has a median and standard deviation parallax of 2.84 mas and 0.36 mas, respectively. For the proper motions, the median and standard deviation \( \pm 0.063 \) mas yr\(^{-1}\) and \( 0.64 \) yr\(^{-1}\) in right ascension and \( \pm 0.05 \) mas yr\(^{-1}\) and \( 0.68 \) yr\(^{-1}\) in declination. The Gaia DR2 astrometry of HD 161734 is \( \alpha = 2.1716 \pm 0.0407 \) mas, \( \delta = -1.623 \pm 0.063 \) mas yr\(^{-1}\), and \( \sigma = -9.432 \pm 0.062 \) mas yr\(^{-1}\). Therefore, we see that this source has a very precise Gaia DR2 astrometry which is beyond the \( 1\sigma \) distribution of the cluster in all the spaces, especially in parallax which is a decisive variable for the membership analysis. However, we find that this source has a photometry that agrees well with the main sequence of the cluster, and the fact that it shows a clear IR excess makes it a good debris-disc candidate member. Future Gaia releases with improved astrometry might rise the membership probability of this source. In any case, the membership of Miret-Roig et al. (2019) has a true positive rate of \( 90\% \), and this source is an example of the objects that could be missing in that list of members.

5.6. 2MASS J17462472+0517213

This source has an excess in MIPS at 24 \( \mu \)m. We cannot confirm the excess with WISE since this source is detected as an upper limit in W4. This is the coolest star for which we detect an IR excess. VOSA finds a best fit with a SED of 5750 K, which is consistent with the Gaia and Smith et al. (2011) effective temperatures and with an early G spectral type.

5.7. HD 161734

HD 161734 was not initially included in our sample because it has a low membership probability in Miret-Roig et al. (2019). However, Smith et al. (2011) and Meng et al. (2017) detected an excess emission from the near- to mid-infrared which motivated us to study the object further. With our new IRAC and MIPS photometric reduction, we also detect an excess. Additionally, we searched the WISE photometry finding an excess consistent with what is seen with Spitzer (see Fig. 10). Smith et al. (2011) mention in their conclusions that this source may be a binary. However, they did not mention on what they based their hypothesis and we ourselves do not find any evidence of a binary nature. Based on its NIR excess, these latter authors also proposed that this source could have a remnant primordial disc. They were able to fit the excess with a 500 K blackbody, suggesting a dusty disc with a radius of 1.7 AU. Considering the members obtained with Gaia in Miret-Roig et al. (2019), the cluster has a median and standard deviation parallax of 2.84 mas and 0.36 mas, respectively. For the proper motions, the median and standard deviation \( \pm 0.063 \) mas yr\(^{-1}\) and \( 0.64 \) yr\(^{-1}\) in right ascension and \( \pm 0.05 \) mas yr\(^{-1}\) and \( 0.68 \) yr\(^{-1}\) in declination. The Gaia DR2 astrometry of HD 161734 is \( \alpha = 2.1716 \pm 0.0407 \) mas, \( \delta = -1.623 \pm 0.063 \) mas yr\(^{-1}\), and \( \sigma = -9.432 \pm 0.062 \) mas yr\(^{-1}\). Therefore, we see that this source has a very precise Gaia DR2 astrometry which is beyond the \( 1\sigma \) distribution of the cluster in all the spaces, especially in parallax which is a decisive variable for the membership analysis. However, we find that this source has a photometry that agrees well with the main sequence of the cluster, and the fact that it shows a clear IR excess makes it a good debris-disc candidate member. Future Gaia releases with improved astrometry might rise the membership probability of this source. In any case, the membership of Miret-Roig et al. (2019) has a true positive rate of \( 90\% \), and this source is an example of the objects that could be missing in that list of members.
In the following, we compare the disc fractions obtained in this study with other young clusters and associations. This comparison should be regarded as tentative and taken with caution given that the various studies quoted below have very different levels of sensitivity and/or completeness (see Wyatt 2008; Hughes et al. 2018, and references therein for a detailed discussion on the difficulties related to such comparisons). Additionally, the level of completeness and contamination in the list of members differs from one study to another and most of them are based on pre-Gaia members lists.

Gorlova et al. (2007) performed an analogous study to the one presented here for the NGC 2547 open cluster. This is a very similar cluster in terms of age (30 Myr, Jeffries et al. 2006) and distance (400 pc). Gorlova et al. (2007) imaged the inner 1° × 1° regions which at the distance of the cluster corresponds to ~50 pc, and were complete down to a spectral type of late-F in MIPS1. They found a 8–A9 excess fraction of ~44% and a F0–F9 excess fraction of ~33%. These values are significantly larger than what we find in IC 4665, although the authors do not provide uncertainties. We believe that the same reasons we discussed to explain the differences with the study of Smith et al. (2011) could apply to this discussion. Indeed, we checked that around 40% of their MIPS sample could be contaminants according to the Gaia DR2 astrometry.

Gorlova et al. (2006) studied the disc population of the intermediate-age Pleiades cluster (120 Myr). These latter authors analysed Spitzer MIPS1 data for an area covering the central 2° × 1° area of the cluster which at the distance of the Pleiades corresponds to an area of 14 pc². Data were complete down to a spectral type of K3, or even M2 in the regions with less nebulous objects. The authors estimated the debris disc fraction of B–A members to be ~25%, which is very similar to the value found in IC 4665 and is consistent with a slow evolution of the 24 µm excess in debris discs, with a characteristic timescale of 150 Myr (e.g. Siegler et al. 2007; Gorlova et al. 2006). However, the proximity of the Pleiades with respect to IC 4665 leads to a significantly smaller spatial coverage of this cluster, hindering a proper comparison of the disc fractions.

In Fig. 11 we compare the disc fractions obtained in this study with several nearby clusters and associations reported in a recent work by Chen et al. (2020) for early- and solar-type stars. We see that our disc fraction for B–A stars is compatible with the disc evolution trend defined by the other clusters. The disc fraction we measure at 30 Myr is compatible within the uncertainties with clusters of 15–20 Myr (Upper Centaurus Lupus, Lower Centaurus Crux, and the β Pictoris moving group) and with the Pleiades at 125 Myr. In the case of solar-type stars, our disc fraction is smaller than that from clusters of ~20 Myr that are closer than 150 pc. Interestingly, our disc fraction is similar to the one reported in younger clusters (5–10 Myr) at similar distances (Orion OB1a and Orion OB1b).

Our Spitzer photometry of IC 4665 only covers the central 1° × 1° of the cluster (see Fig. 1). However, according to the most complete membership analysis to date (Miret-Roig et al. 2019), the cluster has a size of at least 3° radius. We estimated that MIPS1 observations only cover 55% of the B–A stars of the cluster by comparing the spatial distribution of all the B–A members in a circle of 3° radius (whole cluster area) with the same population in the area covered by MIPS data (1° × 1°). Therefore, the disc fractions we obtain with MIPS1 are in principle only valid for the central part of the cluster. Since we also have WISE photometry, which covers all the area occupied by the cluster (a circle of 3° radius in this case) we used it to estimate the disc fraction. We obtain a fraction of 3/14 or 21±12% at 22 µm (W4)

6. Discussion

We estimated that our MIPS photometry is complete down to [24] ≤11.8 (late-B to mid-K, see Sect. 2.3) in our sample. In this spectral range and in the central 1° × 1° area covered by MIPS (37 pc²), the disc fraction of IC 4665 is 5/32 or 16 ± 7%. This fraction is smaller (although compatible within the uncertainties) than the 27 ± 3% rate reported in a previous study of this cluster, covering the same field of view and magnitude range (Smith et al. 2011). The main reasons for this difference are our improved image-processing techniques (see Sect. 2), the fact that we only provide PSF photometry and Smith et al. (2011) mixed PSF and aperture photometry, and the different lists of members. We discarded most of the candidates of these latter authors because their MIPS1 photometry was systematically brighter than ours (10 sources were rejected for this reason), and/or the sources are no longer classified as members after the analysis of the Gaia DR2 astrometry (3 sources were rejected for this reason).

Many studies in the literature provide the disc fraction for B–A stars and solar-type stars separately in different clusters and star forming regions. To compare our study with these results, we estimated these fractions in our sample. The B–A stars in IC 4665 have an intrinsic colour $G - K_S \leq 0.75$ mag, and in this range the disc fraction becomes 4/17 or 24±10%. If we apply the same selection to the sample of Smith et al. (2011) we obtain a disc fraction of 5/14 or 36±12% for B–A stars. Therefore, in this spectral range we also obtain a smaller disc fraction, although both are consistent within the uncertainties. We only detect one candidate in the spectral range F5–K5 (solar type stars) which results in a disc fraction of 1/11 or 9 ± 9%. Smith et al. (2011) report a disc fraction of 10/24 or 42±13% in the same spectral range which is discrepant with our results. Finally, we note that the disc fractions derived by us for early- and solar-type stars are compatible with the relatively large uncertainties.
in the spectral range late–B to mid–A (see Sect. 2.3). This value is very similar to what we obtain with MIPs at the central region in the same spectral range 2/8 or 25 ± 15%.

7. Conclusions

Here, we present a study of the debris disc population of the 30 Myr open cluster IC 4665. We identified six candidates with IR excess, two of which are new candidates. All of them have 30 Myr open cluster IC 4665. We identified six candidates with

Conclusions

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ter, finding a similar result in the B–A range. We believe that the non-excess locus. We also used the Kurucz atmospheric

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Appendix A: Additional tables and figures

Fig. A.1. \((G - K_s) - (K_s - [24])\) colour-colour diagram of the Pleiades members with good 24 \(\mu\)m photometry from Table 2 of Gorlova et al. (2006). Only the sources classified as non-excess sources by the authors (black points) are used in the fit.

Fig. A.2. Photometric uncertainties at [24] \(\mu\)m as a function of the \(G - K_s\) colour.

Fig. A.3. Same as Fig. 10 for the source HD 161261 which does not present an IR excess. The filled black circles represent the photometric points of the primary, since in these observations the binary system is resolved.

Table A.1. Photometric bands used to detect an IR excess in Sect. 3.

| Object               | G (mag) | Ks (mag) | W1 (mag) | W2 (mag) | W3 (mag) | W4 (mag) | IRAC1 (mag) | IRAC2 (mag) | IRAC3 (mag) | IRAC4 (mag) | MIPS1 (mag) |
|----------------------|---------|----------|----------|----------|----------|----------|-------------|-------------|-------------|-------------|-------------|
| HD 161261            | 8.26 ± 0.05 | 8.04 ± 0.05 | 8.00 ± 0.03 | 7.98 ± 0.02 | 7.75 ± 0.02 | 7.15 ± 0.11 | 7.98 ± 0.02 | 7.75 ± 0.02 | 7.15 ± 0.11 | 7.98 ± 0.02 | 7.75 ± 0.02 |
| HD 161733            | 7.96 ± 0.05 | 7.87 ± 0.05 | 7.85 ± 0.03 | 7.89 ± 0.02 | 7.87 ± 0.02 | 7.69 ± 0.15 | 7.92 ± 0.03 | 7.92 ± 0.03 | 7.92 ± 0.03 | 7.92 ± 0.03 | 7.92 ± 0.03 |
| TYC 428-1938-1       | 11.01 ± 0.05 | 9.95 ± 0.05 | 9.95 ± 0.03 | 9.85 ± 0.02 | 9.85 ± 0.02 | 9.85 ± 0.02 | 9.62 ± 0.18 | 9.62 ± 0.18 | 9.53 ± 0.02 | 9.53 ± 0.02 | 9.53 ± 0.02 |
| 2MASS J17462472+0517213 | 12.67 ± 0.05 | 10.81 ± 0.05 | 10.81 ± 0.03 | 10.81 ± 0.02 | 10.81 ± 0.02 | 10.81 ± 0.02 | 9.87 ± 0.07 | 9.87 ± 0.07 | 9.87 ± 0.07 | 9.87 ± 0.07 | 9.87 ± 0.07 |
| HD 161621            | 8.42 ± 0.05 | 8.46 ± 0.05 | 8.46 ± 0.03 | 8.46 ± 0.02 | 8.46 ± 0.02 | 8.46 ± 0.02 | 8.46 ± 0.02 | 8.46 ± 0.02 | 8.46 ± 0.02 | 8.46 ± 0.02 | 8.46 ± 0.02 |

Notes. Only the sources for which we detect an IR excess are shown. An extended version of this table including all the photometric bands analysed in this work for all the members of IC 4665 is available at the CDS.