Multi-wavelength, spatially resolved modelling of HD 48682’s debris disc

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ABSTRACT
Asteroids and comets (planetesimals) are created in gas- and dust-rich protoplanetary discs. The presence of these planetesimals around main-sequence stars is usually inferred from the detection of excess continuum emission at infrared wavelengths from dust grains produced by destructive processes within these discs. Modelling of the disc structure and dust grain properties for those discs is often hindered by the absence of any meaningful constraint on the location and spatial extent of the disc. Multi-wavelength, spatially resolved imaging is thus invaluable in refining the interpretation of these systems. Observations of HD 48682 at far-infrared (Spitzer, Herschel) and sub-millimetre (JCMT, SMA) wavelengths indicated the presence of an extended, cold debris disc with a blackbody temperature of $57.9 \pm 0.7$ K. Here, we combined these data to perform a comprehensive study of the disc architecture and its implications for the dust grain properties. The deconvolved images revealed a cold debris belt, verified by combining a 3D radiative transfer dust continuum model with image analysis to replicate the structure using a single, axisymmetric annulus. A Markov chain Monte Carlo analysis calculated the maximum likelihood of HD48682’s disc radius ($R_{\text{disc}} = 89^{+17}_{-20}$ au), fractional width ($\Delta R_{\text{disc}} = 0.41^{+0.27}_{-0.30}$), position angle ($\theta = 66.3^{+4.5}_{-4.9}$), and inclination ($\phi = 112.5^{+4.2}_{-4.2}$). HD 48682 has been revealed to host a collisionally active, broad disc whose emission is dominated by small dust grains, $a_{\text{min}} \sim 0.6 \mu$m, and a size distribution exponent of $3.60 \pm 0.02$.

Key words: stars: individual: HD 48682 – circumstellar matter – infrared: stars: planetary systems

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1 INTRODUCTION
Planets and planetesimals (asteroids and comets) are known to be forged during the earliest stages of stellar evolution in dusty, gaseous circumstellar material known as a protoplanetary disc (Lissauer 1993; Wyatt et al. 2015). Once the primordial protoplanetary disc has dissipated and planet formation processes have (mostly) run their course, planetesimal belts are still observable around stars through the detection of scattered light and continuum emission at infrared and millimetre wavelengths from dust produced in collisions between planetesimals. Such systems are therefore referred to as ‘debris discs’; their study forms an integral part of our understanding of the formation and evolution of planetary systems (Wyatt 2008; Matthews et al. 2014; Hughes et al. 2018).

Initial studies into debris discs were mostly limited to the investigation of spatially unresolved photometry (e.g., Backman & Paresce 1993; Wyatt et al. 2007; Kains et al. 2011) and/or mid-infrared spectroscopy (Chen et al. 2006; Beichman et al. 2006; Chen et al. 2014; Mittal et al. 2015). Such data only provided weak constraints on the location and spatial extent of the debris discs. More recently, spatially resolved images particularly from Herschel and ALMA, but also scattered light facilities such as Hubble, GPI, and SPHERE, have revealed the underlying structure within a greater number of discs (e.g. Booth et al. 2013; Pawellek et al. 2014; Moor et al. 2015; Morales et al. 2016; Holland et al. 2017; Matrà et al. 2018). Observations at different wavelengths are sensitive to dust grains with different sizes and temperatures. Scattered light, and near- and mid-infrared wavelengths are sensitive to smaller dust grains whose orbital motions and spatial distribution are influenced by radiation forces; whereas millimetre wavelengths trace larger (cooler) grains whose orbital motions are more weakly affected by radiation forces (Burns et al. 1979). Multi-wavelength,
spatially resolved imaging therefore provides better insight into both the location of planetesimal belts, and the properties of the dust grains generated by those bodies. The combination of imaging and photometric information addresses inherent degeneracies in the modelling of either data set individually (e.g. Marshall et al. 2014), enabling the most detailed possible understanding of these systems’ properties (e.g. Ertel et al. 2012; Löhne et al. 2012; Ertel et al. 2014; Hengst et al. 2017; Geiler et al. 2019).

Debris discs have been detected around hundreds of stars in either scattered light or continuum emission, but a substantial fraction of these systems remain spatially unresolved (e.g. Matthews et al. 2014; Hughes et al. 2018). However, a survey of 34 resolved discs conducted in the far-infrared wavelengths determined relationships between dust grain sizes, minimum grain size \((s_{\text{min}})\) and radiation blowout size \((s_{\text{blow}})\), with stellar luminosities and dust temperatures (Pawellek et al. 2014). These relationships can be applied to understanding unresolved systems. For example, by exploring the ratio of \(s_{\text{min}}/s_{\text{blow}}\) to obtain insights into the nature of dusty grains across a range of environments, and infer the expected extent of those spatially unresolved discs (Pawellek & Krivov 2015).

An increasing number of debris discs have been spatially resolved at millimetre wavelengths in recent years, particularly fuelled by the increased capabilities of ALMA (e.g. previously driven by observations by the JCMT and SMA (e.g. Steele et al. 2016; Holland et al. 2017; Matrà et al. 2018; Sepulveda et al. 2019). Matrà et al. (2018) determined a strong statistical relationship between the stellar luminosity and the measured planetesimal belt radii based on spatially resolved observations of 26 debris discs with the SMA and ALMA. Matrà et al. (2018) suggested there may be a link between CO snow lines in protoplanetary discs and the subsequent locations of planetesimal belts (e.g. Andrews et al. 2018; Pinte et al. 2020).

HD 48682 (56 Aur; HIP 32480) was originally classified as a visual binary in the Washington double-star catalogue (Mason et al. 2001). The star was first identified to have extended excess by the InfraRed Astronomical Satellite (IRAS, Aumann & Probst 1991), although there was confusion as to which star in the system was responsible for the extended emission. It was later discovered that the two stars were not physically associated with each other due to differing proper motions, and Sheret et al. (2004) concluded that the large 60 \(\mu\)m IRAS excess is associated with the ‘primary’ as confirmed from their Submillimetre Common-User Bolometer Array (SCUBA) observation. The primary is referred to as HD 48682 and is classified as G0 V star (Hoffleit & Warren 1995), whilst the secondary is referred to as HD 48682B, is classified as a M0 star and is not a component of this work. HD 48682 was spatially resolved using the Multiband Infrared Photometer (MIPS) camera Rieke et al. (2004) onboard the Spitzer Space Telescope (Werner et al. 2004) at 70 \(\mu\)m (Stapelfeldt et al. 2005).

Extensive archival imaging data sets of HD 48682 are available in the far-infrared and sub-millimetre wavebands. It was observed as part of the Open Time Key Programme Dust around Nearby Stars (Eiroa et al. 2013) with the Herschel Space Observatory (Pilbratt et al. 2010) in six wavebands from 70 to 500 \(\mu\)m with the Photodetector Array Camera and Spectrometer and Spectrometer, and the Photometric Imaging Rceiver instruments (PACS and SPIRE; Poglitsch et al. 2010; Griffin et al. 2010). The Submillimetre Common-User Bolometer Array 2 (SCUBA-2) on the James Clerk Maxwell Telescope (JCMT; Holland et al. 2013) produced images in the wavebands 450 and 850 \(\mu\)m for HD 48682. The Sub-Millimeter Array (SMA), an 8-element interferometer that covers between 180 to 800 GHz (Ho et al. 2004), obtained data in the vicinity of HD 48682 with the receiver band centred on 225 GHz (\(\approx 1.3\ \text{mm}\)).

In this work, we analyse the available far-infrared and sub-millimetre images of HD 48682 in combination with archival photometric and the mid-infrared spectroscopic data, to seek a better understanding of the architecture and composition of HD 48682’s debris disc. In Section 2, we describe the observations, the associated modelling and analysis of HD 48682. In Section 3, the results of the analysis of the Spectral Energy Distribution (SED), images and radial profiles at Herschel/PACS 70/100/160 \(\mu\)m are presented along with calculations of the disc’s observational properties: dust temperature \(T_{\text{dust}}\), disc radial extent \(R_{\text{dust}}\) (both from the blackbody assumption and the resolved/deconvolved images), and disc fractional luminosity \(L_{\text{dust}}/L_\star\). We discuss the fitting of the imaging and photometric observations using the 3D MCMC radiative transfer code Hylas (Robitaille 2011) and the determination of most probable disc parameters and associated uncertainties using emcee (Foreman-Mackey et al. 2013). In Section 4, we discuss the state of the disc in comparison with other studied systems and the potential disc brightness asymmetry observation. Finally, in Section 5, we present our conclusions.

Whilst these research procedures have been used to study various circumstellar discs, they have not been employed in this combination specifically for debris discs. We view this as a first paper of a series to provide a foundation in the analysis of debris discs. This paper will be followed by Marshall et al. (2020, in review) that will employ these procedures for a number of debris disc systems.

2 OBSERVATIONS AND ANALYSIS

The observational data for the HD 48682 system are presented in this section. This includes describing the characterisation of the host star through fitting a stellar photosphere model, a summary of the ancillary photometry compiled for the SED, and a description of the reduction of the Herschel/PACS observations and subsequent analysis. The compiled SED for HD 48682, the scaled photospheric model, and the blackbody fit to the dust excess are shown in Figure 1.

2.1 Stellar parameters

HD 48682 is a nearby \((d = 16.65 \pm 0.07 \text{ pc}; \text{Gaia Collaboration et al. 2018})\) G0 main-sequence star with an effective temperature \(6086 \text{ K}\) (Eiroa et al. 2013). Several attempts have been made to determine the age of HD 48682, yielding a wide range of results. Most recently, Eiroa et al. (2013) obtained two distinct estimates of the age of HD 48682 through the use of X-ray observations and Ca II as tracers. These two methods yielded ages of 1.38 and 6.38 Gyr respectively. Where isochrones were used to determine stellar age, Perrin et al. (1977), from a sample of 138 stars, and Holmberg et al. (2009b), from a sample of 16 682 F and G stars, calculated ages of 8.91 Gyr and 3.2\(^{+1.4}_{-1.2}\) Gyr respectively. These calculated stellar ages are used with caution as Holmberg et al. (2009b) states that isochrones are very sensitive to the stars effective temperature and metallicity. However, all methods agree that HD 48682 stellar age is at least 1 Gyr. A summary of the stellar physical properties for HD 48682 is given in Table 1.

The stellar photospheric contribution to HD 48682’s SED was modelled using the closest matching model \((T_\text{eff} = 6030 \text{ K}, \log g\)
The optical Johnson and Johnson-Cousins (Just & Jahrei 2008); (3) Johnson-UKIRT, Gezari et al. (1999); (4) Holmberg et al. (2009a); (5) Perrin et al. (1977); (6) Takeda et al. (2007).

\[ \frac{\mu m}{4.39, [\text{Fe/H}]} = 0.00 \text{ available from the Castelli-Kurucz atlas}^{1} \text{(Castelli & Kurucz 2004). The selected photospheric model was scaled to the optical and infrared observations at wavelengths between 0.4 and 10 \mu m, weighted by their uncertainties, using a least squares fit (\chi^2 = 5.28, \chi^2_{red} = 1.06). HD 48682's assumed stellar radius from this scaling of the photospheric model was determined to be 1.23 R_\odot, consistent with the estimate of 1.18^{+0.14}_{-0.02} R_\odot calculated by Takeda et al. (2007).}

\[ 2.2 \text{ Ancillary data} \]

To model the SED of HD 48682, the Herschel and SCUBA-2 photometry were supplemented with a broad range of observations from the literature spanning optical to far-infrared wavelengths. A summary of the collected photometry is shown in Table 2.

The optical Johnson BV photometry were taken from the Hipparcos Input Catalogue (Turon et al. 1993), whilst the near-infrared Cousins I and Johnson JHK, photometry were taken from the Sloan Digital Sky Survey (SDSS; Just & Jahrei 2008) and United Kingdom Infra-Red Telescope (UKIRT; Gezari et al. 1999), respectively. We opted not to use the 2MASS photometry because of lower precision and note that the 2MASS images were saturated by the secondary star (Sheret et al. 2004).

The mid-infrared photometry that were used were taken from the AKARI IRC all-sky survey at 9 and 18 \mu m (Ishihara et al. 2010) and the WISE survey at 3.4, 4.6, 12, and 22 \mu m (Wright et al. 2010). Colour corrections were applied to the AKARI IRC measurements assuming a blackbody temperature of 6000 K (factors of 1.180 at 9 \mu m and 0.990 at 18 \mu m) and applied to the WISE photometry assuming a Rayleigh-Jeans slope. A correction (factor of 0.873) was applied before the flux conversion to the WISE 4.6 \mu m catalog (magnitude) value because of a known photometric bias (Tisserand et al. 2018). It can be seen that the AKARI IRC 18 \mu m measurement has a slight excess, which could be attributed to either a warm component of the debris disc (although this was ruled out by Pawellek et al. 2014), the secondary star nearby (although the 9 \mu m measurement appears to be unaffected), or, given the wavelength range (13.9 - 25.6 \mu m) of the corresponding filter, the initial rise of the cold excess emission from \sim 20 \mu m (see Figure 1).

A Spitzer InfraRed Spectrograph (IRS; Houck et al. 2004) low-resolution spectrum spanning 5 to 36 \mu m was taken from the CASSIS database\(^2\) (Lebouteiller et al. 2011). The IRS spectrum was scaled by the weighted mean differences at wavelengths <10 \mu m, where significant excess from the debris disc is not expected. The IRS spectrum was scaled using synthetic photometry extracted from the spectrum using the AKARI IRC9 and WISE W3 filter passbands, from which we determined a best-fit scaling factor of 0.94. For it to be included in the SED modelling process, the IRS spectrum was binned with a weighted average mean (with the associated uncertainty) to calculate synthetic photometry at 30, 32, and 34 \mu m. These values were used to trace the rise in the excess emission from the dust above the photosphere at mid-infrared wavelengths (see Section 3.2 for details).

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\[ ^1 \text{Castelli-Kurucz models can be obtained from: http://www.stsci.edu/hst/observatory/crds/castelli_kurucz_atlas.html} \]

\[ ^2 \text{The Cornell Atlas of Spitzer IRS Sources (CASSIS) is a product of the Infrared Science Center at Cornell University, supported by NASA and JPL.} \]
Figure 1. SED of HD 48682. Circle data points are the measured photometry for HD 48682 ranging from optical to sub-millimetre wavelengths. Photometry between 0.4 to 10 μm were used to scale the stellar photosphere model represented by the (black) dashed line. The broad (blue) solid line is the Spitzer IRS spectrum. The light blue data points represent the Herschel photometry. The purple data points represent the SCUBA-2 photometry. Solid triangle data points show the upper limit of 450 μm and 500 μm flux values. Solid Circle (red) data points represent the stellar subtracted values to calculate the (cold) dust contribution, estimated as a 57.9 K blackbody, which is represented as a (green) dotted line. The total flux and disc-only contribution are shown as solid and dot-dashed green lines, respectively. See Section 3.3 for the further details.

Table 3. Summary of Herschel PACS and SPIRE observations of HD 48682.

| Instrument | Observation ID | Wavelengths [μm] | Observation Date |
|------------|----------------|------------------|------------------|
| PACS       | 1342219021/22  | 70/160           | 19-Apr-2011      |
| PACS       | 1342206334/35  | 100/160          | 12-Oct-2010      |
| SPIRE      | 1342204066     | 350/450/500      | 5-Sep-2010       |

2.3 Herschel data

HD 48682 was observed as part of the Herschel Open Time Key Programme DUNES (DUST around Nearby Stars; KPOT_ceiroa_1: Eiroa et al. 2013). PACS scan map observations of HD 48682 were taken in both 70/160 μm and 100/160 μm channel combinations. SPIRE observations were taken in the 350/450/500 channel combination. The log of Herschel observations is given in Table 3.

The Level 3 image products of the Herschel/PACS data were directly downloaded from the Herschel Science Archive 3. The image scales for these final mosaicked images were 1.7′/pixel for the 70 and 100 μm images, and 3.2′/pixel for the 160 μm image.

Fluxes were measured using a standard Aperture Photometry routine implemented in the Herschel Interactive Processing Environment 4 (HIP - user release 15.0.1 and PACS calibration version 78 - the latest available public release at the time; Ott 2010). The circular aperture radii were chosen to be 12 pix (19′.2), 11 pix (17′.6), and 9 pix (28′.8) for the 70, 100, and 160 μm maps respectively. To estimate the value of the sky noise background we first measured the median values of ten randomly placed 25x25 pixel sub-regions for 70 and 100 μm images and 10x10 sub-regions for 160 μm image to avoid HD 48682 and borders pixel values - similar to the method used in Hengst et al. (2017). To determine a final sky noise estimate for each image we adopted the method outlined in Eiroa et al. (2013). The mean of median sub-region values was used as the estimate of the dispersion of background flux (σ_{pix}). The sky noise was calculated by multiplying σ_{pix} by the product of the square root of the number of pixels (√N_{pix}) used in the respective circular apertures in each image for the flux estimate (Poisson noise) and the correlated noise component (σ_{corr} = 3.7) as determined by Eiroa et al. (2013). To yield final photometric values, the calculated sky noise values were subtracted from the flux estimates measured in each circular aperture to yield the source flux of HD 48682 for PACS images.

The source flux values were scaled by appropriate aperture correction factors of 0.859 (19′.2), 0.835 (17′.6) and 0.849 (29′.8) at 70, 100 and 160 μm photometry, respectively (Balog et al. 2014). It is noted that it may be contentious when applying aperture corrections calculated for point sources when working on extended sources, however, this method has been adopted widely in the literature (e.g. Hengst et al. 2017). The flux uncertainties were estimated from the standard deviation of the median values of the sub-regions respectively for each image, and then multiplied by the Poisson noise distribution and the correlated noise value as before. The final PACS fluxes and associated uncertainties are shown in Table 2, alongside the PACS estimates from Eiroa et al. (2013) for comparison.

It was discovered that the deconvolution of the 70 μm map revealed background or noise sources beyond the NW and SE arms of the disc that may contribute to confusion noise (see Section 3.1.3 for details). As the circular aperture used in the photometry image would cover these sources, then the flux estimate of these sources (σ = 0.03 Jy) was used to calculate the final uncertainty corresponding to the 70 μm flux.

3 RESULTS

In this section, we present the results of our analysis of HD 48682’s disc. We first examine the Herschel/PACS images for evidence of extended emission, followed by the application of a deconvolution routine to ascertain the disc extent and geometry. The additional photometric points were combined with the ancillary data and the measured radial extent from the images to model the disc, by fitting the excess emission with a modified blackbody model, employing an invariable Markov Chain Monte Carlo analysis, and applying a 3D continuum Gaussian model from which we deduce the disc structure and dust grain properties. We also present SCUBA-2 and SMA sub-millimetre image data pertaining to HD 48682.

3.1 Resolved Images

HD 48682 was resolved in the far-infrared wavebands by the Herschel/PACS instrument (Poglitsch et al. 2010) showing the extent of the disc for wavelengths 70, 100, and 160 μm (see top row in Figure 2). The 70 and 100 μm maps were originally 0.6250 pixels per 1′′.
whilst the 160 µm map was 0.3125 pixels to 1′′. All maps were re-
sampled to 1 pixel to 1′′ for comparison analysis. HD 48682’s disc
was resolved by JCMT/SCUBA-2 observations at 450 and 850 µm,
where the images were also re-sampled to 1 pixel to 1′′(Holland et al. 2017). We also located six sets of archival SMA observa-
tions of HD 48682 taken at ≈ 230 GHz (Project ID 2015B-s014,
P.I. Macgregor). Four out of the six SMA archival observation sets
contained useable data.

3.1.1 Herschel Stellar position

The optical position of HD 48682 is 6h46m46s.44 +33°34′09.97 for
the 100 µm source utilising the proper motions from Gaia Collabo-
ration et al. (2018). A 2D Gaussian profile was fitted to HD 48682,
allowing for rotation and ellipticity. The centre of the disc profile
was measured to within 1′′/0 from the optical position, which is well
inside the Herschel absolute pointing accuracy of 2′/5 at the 1-σ
level (Sánchez-Portal et al. 2014). For the deconvolution process
presented here, we have assumed that the star’s position is the cen-
tre of the 2D Gaussian profile.

3.1.2 Herschel Radial profiles and deconvolution

The extent of the 70 µm source was determined by fitting the semi-
major and -minor axes of an ellipse; whilst the extent of the semi-
major and -minor axes of the 100 and 160 µm maps were derived
from the FWHM of model 2D Gaussian profiles along the major
and minor axes. The orientation (position angle, inclination) of the
disc was consistent across all three images. The disc radial extent
is likewise consistent, after accounting for the larger PSF/FWHM
at longer wavelengths, suggesting the disc is well-resolved by Her-
schel.

To determine stellar contribution and to reveal debris disc struc-
ture, a reference point spread function (PSF) was used. We
adopted a similar technique applied by Hengst et al. (2017), simi-
lar to the methods used in Liseau et al. (2010) and Marshall et al.
(2011). Observations of a fiducial star, α Böötis (HD 124897, Arc-
turus), was selected, reduced and rotated to the same position angle
observed for HD 48682, which was used as the instrument PSF.
This PSF was scaled to expected stellar photospheric flux corre-
sponding to all three Herschel/PACS wavebands, to then be centred
on HD 48682’s position and subtracted away from the respective
original Herschel/PACS maps. This image result was then decon-
volved with the instrument PSF by the Lucy-Richardson method
(Richardson 1972; Lucy 1974). See bottom row of Figure 2 for the
deconvolved images.

After deconvolution, the semi-major and -minor axes of the
disc were measured by fitting an ellipse to the region of the map,
centred on HD 48682, which exceeded a 3-σ threshold. The semi-
major and -minor axes measured in all deconvolved images were
relatively consistent, although slightly larger in in the 70 µm de-
convolution. This could be attributed to the 3-σ ellipse fit capturing
what appears to be an extension branches of emission in the 70 µm
map just beyond both the SE and NW branches of HD 48682 disc.
The distances from the star centre to the centre of the rings (both
along NW and SE branches) were measured by fitting an ellipse to
the (image) clump. The coordinates of the centre of the ring was
taken as the centre of the fitted ellipse. Radial profiles are presented
in Figure 3 and a summary of corresponding measurements is pre-
sented in Table 4.

3.1.3 Additional sources in the 70 µm map

The 70 µm deconvolution appears to have revealed unknown
sources beyond both NW and SE ansae (see Figure 3) away from
the centre of HD 48682, which can be seen in Figure 2 as either an
extension of the disc, background contamination, or random noise
peaks. If these unknown sources are either background sources or
noise peaks (i.e. confusion noise), then the corresponding flux es-
timate of 70 µm band would now be contaminated due to the ra-
dius of the photometric aperture used (12′′). Therefore, increasing
the uncertainty in flux density measured in the aperture photometry
conducted for the 70 µm source.

3.1.4 Residuals

To determine any discernible architecture of HD 48682, models
of the disc at each Herschel/PACS and SCUBA-2 450 µm wave-
band were created using the fitted three-dimensional dust contin-
uum model that was used in the radiative transfer code (see Section
3.3), along with the disc orientation (111°) and inclination (58°)
values determined from deconvolution of the 100 µm source. These
models were further scaled to the expected flux density of the disc
corresponding to their wavelength. These models were then sub-
tracted from their respective original maps after removal of the stel-
lar component by subtraction of a scaled PSF centred on the stellar
location. The original images after stellar subtraction, the disc mod-
els, and residuals for all four wavebands are presented in Figure 4.
We note here that the SCUBA-2 images provided by Holland et al.
(2017) are available online in ‘.png’ format. The ‘original’ image
Corresponding to the SCUBA-2 450 µm waveband was created by
reading in the pixel numbers from the ‘.png’ image into a 2D image
array. A synthetic PSF was constructed by using the 2D Gaussian
model described in Dempsey et al. (2013) as a guide to create the
corresponding convolved disc model at 450 µm.

Both the 70 and 100 µm sources show a brightness asymmetry
with the stronger positive signal along the SE arm, with up to a 3-σ
detection for the 100 µm source. This can also be confirmed by the
radial profiles. Asymmetry in the 70 µm source could be attributed
to the background sources that were detected and/or more small
gains being stirred. There was no noticeable asymmetry detected
in the 160 µm image, probably due to lower signal-to-noise of the
disc and the larger beam FWHM, but rather we see a faint halo of
residual extended emission surrounding the system. This might im-
ply the disc model used is too compact, such that we are tracing
a different grain population at 160 vs. 100 µm which has a more
extended spatial distribution. However, the halo was not detected
with any statistical significance and therefore we are not confident
that this is a real component of the debris disc architecture. For the
SCUBA-2 450 µm image the model appeared to adequately repli-
cate the disc, highlighting a 2-σ source near the SE ansa after model
subtraction.

3.2 Disc architecture

We assume HD 46682 has only a cold-component debris belt be-
cause the SED revealed no significant excess emission at mid-
infrared wavelengths ≤ 20 µm, as can be seen in Figure 1.

5 SONS Legacy Archive:
https://www.canfar.net/citation/landing?doi=17.0005
Figure 2. Original *Herschel* resolved image maps of HD 48682 (top row), the Lucy-Richardson deconvolved images of the original maps after star subtraction (bottom row). The star’s position is represented by a white cross. The instrument beam size (FWHM) is represented by the circle in the bottom left-hand corner for each image. The additional sources, which could be regarded as an extension of the disc, background contamination, or noise peaks in the 70 µm deconvolution, are represented by white plus-signs. Orientation of the images is north up, east left. The images have been re-scaled to 1′′ pixel$^{-1}$. The colour scale bar is in units of Jy/arcsec$^2$. The image RMS (in Jy/arcsec$^2$) values are $2.9 \times 10^{-4}$ at 70 µm, $2.3 \times 10^{-4}$ at 100 µm, and $1.3 \times 10^{-4}$ at 160 µm.

Figure 3. Radial profiles showing relative flux density as a function of arcsec for HD 48682 along the semi-major (left) and semi-minor (right) axes of the disc. The (red) dashed lines are the measured profile either side of the disc centre along each axis; the (red) solid error bars mark the mean profile between each axis. The (black) dashed lines and the (black) dashed-dotted lines are the deconvolved disc profiles along the NW arm and SE arm respectively for the long axis; along the NE extent and SW extent respectively for the short axis. The deconvolved radial profiles have all been scaled to start at a relative value of 1.0 per arcsec for reference. The solid black line is the subtracted stellar profile, which has not been scaled for reference between each map.

Table 4. Measurements of HD 48682’s disc extent, orientation, and inclination.

|                      | 70µm | 100µm | 160µm |
|----------------------|------|-------|-------|
| **Original PACS Maps** |      |       |       |
| Semi-major ["]      | 9.7 ± 0.9 | 11.3 ± 0.9 | 13.5 ± 2.3 |
| Semi-major [µ]       | 162 ± 15 | 189.1 ± 15 | 226.9 ± 38 |
| Semi-minor ["]      | 5.6 ± 0.8 | 6.4 ± 0.7 | 7.5 ± 1.7 |
| Semi-minor [µ]       | 93 ± 13 | 107.0 ± 12 | 125.2 ± 28 |
| Inclination Angle ["] | 54.9 ± 5.2 | 55.6 ± 5.1 | 56.2 ± 8.3 |
| Position Angle ["]  | 111.1 ± 0.5 | 110.4 ± 0.5 | 102.8 ± 1.0 |
| **Deconvolved Images** |      |       |       |
| Semi-major ["]      | 13.2 ± 0.5 | 13.0 ± 0.5 | 12.8 ± 1.0 |
| Semi-major [µ]       | 221.5 ± 8.4 | 218.0 ± 8.4 | 214.9 ± 16.4 |
| Semi-minor ["]      | 8.2 ± 0.5 | 6.9 ± 0.5 | 7.2 ± 1.0 |
| Semi-minor [µ]       | 137.0 ± 8.4 | 115.4 ± 8.4 | 120.1 ± 16.4 |
| Inclination Angle ["] | 51.8 ± 6.9 | 58.0 ± 2.2 | 56.0 ± 7.7 |
| Position Angle ["]  | 110.8 ± 0.5 | 111.4 ± 0.5 | 120.0 ± 1.0 |
| NW Arm ["]          | 4.7 ± 0.5 | 5.6 ± 0.5 | 5.3 ± 1.0 |
| NW Arm [µ]           | 77.9 ± 8.0 | 93.1 ± 8.0 | 88.4 ± 17 |
| SE Arm ["]          | 4.8 ± 0.5 | 5.1 ± 0.5 | 4.7 ± 1.0 |
| SE Arm [µ]           | 79.8 ± 8.0 | 84.8 ± 8.0 | 79.1 ± 17 |

We then fitted a single (temperature) component, modified blackbody to the photometry at wavelengths where significant excess was measured (> 3-$\sigma$), to calculate observational properties of...
Figure 4. Images of HD 48682 indicating potential asymmetry in 70 and 100 $\mu$m bands, further extension of emission in the 160 $\mu$m band, and SCUBA-2 450 $\mu$m for comparison. Left: The original image with stellar subtraction. Middle: The convolved model. Right: shows the residuals normalised by the RMS. Solid contours represent 2.0, 2.5, 3.0-$\sigma$ level where available, and the dot-dashed contours show the 0.0-$\sigma$ level where available to confirm disc subtraction. Image orientation is north up, east left. The images have the same scale of 1” pixel$^{-1}$. The colour scale bar is in units of Jy arcsec$^{-2}$ for Columns 1 and 2. The colour bar scale for Column 3 are scaled to the respective RMS (in Jy arcsec$^{-2}$) values in each residual image, which are as follows: $2.3 \times 10^{-4}$ at 70 $\mu$m, $2.6 \times 10^{-4}$ at 100 $\mu$m, $3.6 \times 10^{-4}$ at 160 $\mu$m, and $1.4 \times 10^{-3}$ at 450 $\mu$m.

The dust temperature, disc extent, and fractional luminosity ($T_{\text{dust}}$, $R_{\text{dust}}$, $L_{\text{dust}}/L_*$). A least-squares fit to the photometry weighted by the uncertainties calculated a fractional luminosity of $L_{\text{dust}}/L_* = (7.2 \pm 0.4) \times 10^{-3}$ and temperature of $T_{\text{dust}} = 57.9 \pm 0.7$ K, in line with previous estimates of the disc brightness by Eiroa et al. (2013).

If we assume the dust acts like a blackbody source then we can estimate its radial location, which is referred to as the blackbody radius of the debris disc. The measured blackbody temperature of HD 48682’s disc is equivalent to an orbital radius of $R_{\text{dust}} = 31.2 \pm 1.1$ au. A comparison with the mean distances of the NW and SE branches in the 70 and 100 $\mu$m deconvolutions (78.9 $\pm$ 11.3 au) and (89.0 $\pm$ 11.3 au) respectively, reveals that the ratio of the actual to blackbody radii to be $\Gamma = 2.7 \pm 0.5$. This is lower than expected ($\Gamma = 6.2 \pm 1.1$) when assuming pure astrosilicate grains ($\rho_* = 3.3$ g/cm$^3$) determined from the models of Pawellek & Krivov (2015).

We determine the disc architecture through image analysis by initially assuming it is well approximated by a single Gaussian annulus, described by five parameters – flux density $F_{\text{disc}}$, radius $R_{\text{disc}}$, fractional width $\Delta R_{\text{disc}}$, inclination $\theta$, and position angle $\phi$. Here we have presented results based on fitting the model to the 100 $\mu$m image data alone. We note that similar values for the disc architecture are obtained by fitting the 70 $\mu$m data, but with greater uncertainties due to the lower signal-to-noise of the observation at that wavelength.

To determine the maximum likelihood values for each model we adopt a Bayesian approach using the affine invariate Markov
Figure 5. Corner plot illustrating the outcome our MCMC analysis carried out with emcee. A single Gaussian annulus was used to model the disc, and convolved with a PSF before comparison with the Herschel/PACS 100 µm images. In total 125,000 realisations (250 walkers, 500 steps) were made, with the first 200 steps of each chain discarded as burn-in, see text for further details.

The initial values for the model disc parameters were determined from the measured flux density and a 2D-Gaussian fit to the source brightness profile, except for the fractional width of the disc (ΔR_{disc}), which was initially set as 0.2. The distribution of initial conditions were likewise based on observed properties of the disc, or instrumental limits. The instrument calibration uncertainty for the SCUBA-2 450 µm was calculated to be approximately 12% (Dempsey et al. 2013). The disc flux density of HD 48682 at 450 µm was measured to be about 32 mJy/beam, with an image RMS of 4.7 mJy/beam (Holland et al. 2017). Therefore, the disc...
flux density was constrained to lie within ±20% of the measured value. The disc radius was constrained to lie between an extent equivalent to half the beam FWHM (i.e. the source must be spatially resolved) and twice the measured FWHM from the 2D Gaussian fit. The fractional disc width was given free range between 0.1 and 0.9. The disc position angle (0–180°) and inclination (0–90°) were both constrained to lie within their respective ranges.

To construct an objective function, we sum the residuals (observation - convolved model) of each realisation for all pixels within a mask. The mask is defined in the following manner. We first identify pixels in the observed image with flux density values greater than 3-σ lying within a circular region of radius 3×FWHM centred on the star. This initial mask is then convolved with the instrument PSF to extend it to adjacent regions to avoid over-fitting the model to the central regions of the source brightness distribution. The final mask area thus comprises all pixels of the convolved mask with values > 0.1.

We ran a total of 125,000 realisations of the model with 250 walkers and 500 steps. We used the first 200 steps as a burn-in for the MCMC chains and calculated the probability distributions from the final 75,000 realisations. From this analysis we determine the maximum likelihood disc parameters to be \( R_{\text{disc}} = 305^{+40}_{-30} \text{ mJy} \), \( R_{\text{disc}} = 89^{+17}_{-20} \text{ au} \), \( \Delta R_{\text{disc}} = 0.41^{+0.27}_{-0.20} \), \( \theta = 66.7^{+5.3}_{-4.9} \), \( \phi = 112.5^{+4.2}_{-4.1} \). These values are consistent, within uncertainties, with estimates previously published in the literature based on the same data set (see Eiroa et al. 2013). The emcee disc values are presented in Table 5 to compare with the Hyperion RT values (see Section 3.3).

The inferred disc radius from this work is consistent with the predicted value \( R_{\text{disc}} = 81.2^{+8.3}_{-8.1} \text{ au} \) for a star with the same luminosity as HD 48268, \( L_\star = 1.752 L_\odot \) based on the relation determined in Matra et al. (2018) from a sample of millimetre-resolved debris discs. This consistency is satisfying, given that even at far-infrared wavelengths the peak of dust emission from a disc should still roughly trace the planetesimal belt location in a system (Pawelek et al. 2019). Since the disc is bright for its age \((L_{\text{disc}}/L_\star) \geq 10^{-3} \), we might infer that the broad disc is indicative of some stirring.

### 3.3 Radiative transfer

We use the radiative transfer (RT) Monte-Carlo code, Hyperion (Robitaille 2011), to simultaneously fit the extended emission and SED of HD 48682. Hyperion allows the user input a three-dimensional dust continuum model, setting this apart from the typical power-law radial distribution models.

\[
D_\lambda(r, h) = \exp \left[ -\frac{r - r_m}{\sqrt{2} r_e} \right]^2 \times f(r, h) \tag{1}
\]

\[
f(r, h) = \frac{1}{2} \exp \left[ -\frac{|h|}{h_m} \right]^2 \tag{2}
\]

Equation 1 shows the distribution of the density of dust grains: \( r \) is the radial position, \( r_m \) is the mean distance, \( r_e \) is the width component of the Gaussian, \( h \) is the height above or below the midplane, and \( h_m \) is the scale height which can modify the thickness of the debris disc in equation 2. For simplicity in this model, \( h_m \) is kept constant at 0.1. We believe the Gaussian belt model used here is adequate to represent the dust distribution, and facilitates comparison with modelling work on similar systems. We assumed a dust composition of astronomical silicate with a density of \( \rho = 3.3 \text{ g/cm}^3 \) (Draine 2003).

### Table 5. Hyperion RT code parameter space results compared with emcee code results. Note \( \nu = (N - f) \) is the number of degrees of freedom. Where \( N \) is the number of data points and \( f \) is the number of variables used in the parameter space.

| Parameter | Range | Distribution | Hyperion | emcee |
|-----------|-------|--------------|----------|-------|
| \( r_m \) (au) | 60 – 100 | Linear | 82.4 \( \pm \) 3 | 89.1 \( \pm \) 17.0 |
| \( r_w \) (au) | 25 – 65 | Linear | 42.2 \( \pm \) 4 | 36.5 \( \pm \) 8.1 |
| \( s_{\text{min}} \) (µm) | 0.5 – 5.0 | Linear | 0.60 \( \pm \) 0.06 | 0.07 |
| \( s_{\text{max}} \) (µm) | — | Fixed | 3000 | — |
| \( q \) | 3.00 – 4.00 | Linear | 3.60 \( \pm \) 0.02 | 0.04 |
| Composition | astron. sil. | Fixed | — | — |
| \( \chi^2 \) | 1.28, 13 | — | — | — |

From the 100 µm deconvolution, the inner and outer edge of the disc were determined to be approximately 28 au and 111 au respectively and from the MCMC fitting, the radius of the disc to be 89.1 \( \pm \) 17.0 au. So, for the purpose of modelling, \( r_m \) was allowed to vary between 60 au and 100 au, whilst the \( r_w \) was allowed to vary between 25 au and 65 au. The constituent grains were represented by a power law size distribution \( (s^{-q} \text{ds}) \) between 60 au and 100 au, whilst the \( s_{\text{max}} \) was fixed at 3000 µm, with the exponent, \( q \), allowed to vary from 3.0 to 4.0.

The Hyperion RT code with the Gaussian debris belt model managed to fit the SED data, specifically fitting to the rising Spitzer IRS spectrum and the falling of the sub-mm data with a \( \chi^2_{\text{red}} \) of 1.28 (13 degrees of freedom); see Figure 1 for the SED fit. The mean distance of the disc lies at \( r_m = 82.4 \pm 2 \text{ au} \) with a \( r_w \) component of 42.2 \( \pm \) 4 au. The minimum dust grain size was calculated to be 0.60 \( \pm \) 0.06 µm, with an exponent of the grain size distribution to be \( q = 3.60 \pm 0.02 \). The uncertainty values for the Hyperion calculations are smaller than the MCMC deviations can be attributed to modelling photometric values as opposed to image data. See Table 5 for the summary of the variables in the parameter space and the fitting results for the Hyperion RT code with the disc parameters from the MCMC analysis are presented for comparison.

### 3.4 Sub-millimetre observations

HD 48682’s disc was resolved by JCMT/SCUBA-2 observations at 450 and 850 µm tracing larger, cooler dust grains. The analysis of the JCMT/SCUBA-2 450 µm image (RMS = 4.7 mJy/beam) by Holland et al. (2017) measured a couple of (marginal) 3-σ peaks of 16.0 mJy (SE) and 16.7 mJy (NW) around the HD 48682’s stellar position of the disc at its ansae. The 450 µm source may reveal a position asymmetry where the location of the SE and NW ansae are measured at 71.6 ± 12.6 au and 97.7 ± 14.5 au respectively. The 850 µm image indicates a brightness asymmetry where the NW peak is brighter.

We calibrated and reduced the usable SMA observations using the MIRIAD software package following the data reduction scripts on the SMA webpage. Uranus was used as the flux calibrator, 0.464+4.48 and 0.455+3.98 were phase calibrators, and 3c84 and 3c273 were used as the bandpass calibrators. The final reduced continuum image was centred on the stellar position with an RMS noise level of 0.2 mJy/beam and a beam FWHM of \( 4'' \times 25'' \times 4'' \). As expected, there was no detection at the stellar position of HD 4862 in the map, but we also find no convincing evidence for detection of the disc in the observation (assuming a predicted flux density of 1.9 mJy, extrapolated from the 850 µm measurement). The level of noise in the image is too high for us to put any constraints on
the disc width or radius, as all plausible architectures from our modelling lie well below the threshold for detection. We can however state that images at least an order of magnitude deeper (10 to 20 $\mu$Jy/beam) are required to detect the disc with any confidence, putting this target beyond the reach of most Northern hemisphere millimetre-wavelength facilities. However, there was a marginal, 3-$\sigma$ (0.6 mJy), detection consistent with the peak position close to the western side of the disc in the JCMT/SCUBA-2 850 $\mu$m image (see Figure 6). We speculate from this that much, if not all, of the asymmetry exhibited in the 850 $\mu$m image can be explained as the result of background contamination from this extended emission.

4 DISCUSSION

Here we place the results of our analysis into context, and examine the origins and the characteristics of the disc around HD 48682.

4.1 State of the disc

From the deconvolution of the Herschel/PACS 100 $\mu$m, we take the observed radius of the disc to be $89 \pm 11$ au, calculated as the mean distance of the two ansae about stellar position. The maximum likelihood probability from the MCMC analysis determined the fractional width is greater than the Solar system’s Edgeworth-Kuiper belt, but not as broad as those discs identified as having sub-structure due to disc-planet interactions, i.e. HD 107146 (Su et al. 2017) and HD 95086 (Marino et al. 2018).

The ratio of observed radius to the blackbody radius of the disc ($\Gamma = 2.9 \pm 0.5$) is smaller than expected if assuming pure astro-silicate grains ($\Gamma = 6.2 \pm 1.1$) when correlated with stellar luminosity (Pawellek & Krivov 2015). On the other hand, if we assume the grains are composed of 50% astro-silicate grains and 50% ice ($\rho_s = 2.3 g/cm^3$, ‘icy grains’), the ratio is closer to what is expected ($\Gamma = 4.0 \pm 0.5$). However, if we consider the upper limit of the radius and fractional width results of the MCMC analysis, we calculate an outer edge of the disc to be at $\approx 142$ au, i.e. considering a disc almost twice its size. Then this distance corresponds to $\Gamma \approx 4.5$, which is getting closer to the expected value when assuming pure astro-silicate grains.

The disc model we assumed to determine the dust properties using Hyperion, based upon a Gaussian annulus, calculated that HD 48682 has a disc of radius $82^{+3}_{-2}$ au and a width of $42^{+2}_{-1}$ au within uncertainties of the measured disc extent of Herschel/PACS 100 $\mu$m deconvolution. The disc was found to be dominated by small grains, assuming a grain composition of astro-silicate, with a size distribution exponent of $3.60 \pm 0.02$ and a minimum grain size of $0.6 \pm 0.1$ $\mu$m when integrated up to a grain size of 3 mm. The size distribution exponent is steep by comparison to previous studies of millimetre detected discs of MacGregor et al. (2016), $q = 3.35 \pm 0.02$, and Marshall et al. (2017), $q = 3.15 \pm 0.09$.
and slightly steeper than the often assumed steady state infinite collisional cascade ($q = 3.5$, Dohnanyi 1969). The minimum grain size is lower than expected when compared to similar systems studied by (Pawellek et al. 2014) and 3-4 times smaller when compared with the blowout size for collisional active discs ($3 < q < 4$, Hughes et al. 2018). Where the grains are acting under the assumption of compact spherical grains of astronomical silicate (Draine 2003).

However, all grains in the HD 48682’s disc (located from ~40 au to ~110 au) could have a composition of dust silicate and water ice since the sublimation distance of these grains is about 27 au (Kobayashi et al. 2011), assuming a sublimation temperature of 100 K for icy grains. Some of this icy contribution to the dust could be expected given the results from similar analyses of Herchel-resolution discs. This suggests the presence of moderately icy grains (Morales et al. 2016) and the increasing number of CO detections in debris discs (e.g. Möör et al. 2013; Greaves et al. 2016; Marino et al. 2016, 2017; Matrà et al. 2017) revealing the planetesimals in exo-Kuiper belt analogues to be volatile rich (although detection of CO in a G-star debris disc is not expected; e.g., Kral et al. 2017; Marino et al. 2020).

HD 48682 is also unusual where the disc is smaller than systems with similar age (Kains et al. 2011; Pawellek et al. 2014), albeit still considered a broad system with a fractional width of ~0.5. Debris discs of age greater (> 1 Gyr) typically have a radial extent of 180 ± 45 au, where the disc of HD 48682 is about half this size. HD 48682’s debris disc is bright in the thermal emission for its age (> 1 Gyr, Kains et al. 2011) when compared to the trends that are expected for Sun-like stars (e.g. Spangler et al. 2001; Decin et al. 2003; Sibthorpe et al. 2018). Collionally active discs produce smaller grains that overheat due to inefficient absorption and scattering properties (Backman & Paresce 1993). Therefore, the compact nature of the disc and the small grains may attribute to a brighter nature of HD 48682’s disc.

4.2 Potential asymmetry and halo

The deconvolved images revealed a potential asymmetry in the separation and brightness of the two ansae from the stellar position. The asymmetry appeared to be verified when the structure and emission from the disc around HD 48682 was not effectively replicated with an axisymmetric disc model for the 70 and 100 $\mu$m sources. However, the disc model was found to replicate the 160 $\mu$m source. In comparison with the JCMT/SCUBA-2 850 $\mu$m image (Holland et al. 2017), it shows a brightness asymmetry but the brighter ansa is on the NW side of the disc, which is on the opposite side to what has been in observed in the far-infrared 70 and 100 $\mu$m sources. Figure 6 (right image) shows the differences in brightness asymmetry by presenting the 850 $\mu$m SCUBA-2 image with a contour overlay of the Herschel/PACS 70 $\mu$m deconvolution. There is also a 2-$\sigma$ detection in the SMA-225 GHz image that is NW of HD 48682’s position (see Figure 7).

The structure being visible in both the JCMT and SMA images could be due to the emission originating from a brightness asymmetry within the disc. If so, this may indicate that the grains may be spatially segregated into different orbital and (possibly) radial locations according to their size. If we assume the NW ansae in the SCUBA-2 850 $\mu$m image is real, then this may be an example of apocentre glow (e.g. Pan et al. 2016). Assuming the background galaxy contamination of 1.2 mJy/beam (Holland et al. 2017) in the NW peak and little or no contamination in the SE peak, then rough approximations of the fluxes of apocentre and pericentre peaks are about ~1.6 mJy/beam and ~1.3 mJy/beam respectively. The eccentricity of the disc at 850 $\mu$m is estimated to be about 0.23 by using the apocentre/pericentre flux ratio to eccentricity relationship derived by Pan et al. (2016). This value is similar to eccentricity calculated from the 450 $\mu$m image of 0.19 using apocentre and pericentre distance values.

The presence of non-axisymmetric structure (eccentricity, brightness asymmetry) in a disc often attributed to perturbation of the disc by an unseen companion. As a relatively old system (> 1 Gyr), a brightness asymmetry in HD 48682’s disc would be of intense interest regarding the stirring of planetesimal belts at late times, such as the proposed Late Heavy Bombardment in the Solar system (Tera et al. 1974; Lowe & Byerly 2018), or the bright disc around HD 10647 (Schippler et al. 2016). However, the brightness asymmetry is potentially due to contamination (from e.g. Galactic cirrus emission or a background galaxy). Therefore, we cannot draw any definitive conclusions regarding the shape of the disc based on the available observations.

5 CONCLUSION

In this work, we have presented archival far-infrared (Herschel/PACS) and sub-millimetre (JCMT/SCUBA-2) observations of the debris disc around HD 48682. These images have revealed emission from a disc extended along both its semi-major and semi-minor axes in all four wavebands. The disc extent was determined by MCMC analysis of the 100 $\mu$m image to be $89^{+17}_{-10} \pm 4.2$ au with an inclination of $66.3^{+1.1}_{-0.9}$ at a position angle of $112.4^{+1.8}_{-0.4}$.

The location of the cold debris belt surrounding HD 48682 was measured to have a mean distance of $83.4 \pm 20.4$ au and $84.6 \pm 19.2$ au in the Herschel/PACS and SCUBA-2 450 $\mu$m images, respectively. This was verified by modelling of the disc using codes HYPERION to model the disc and MCMC to infer the maximum probability model for the disc and its uncertainties. The measured planetesimal belt radius is consistent with other systems of
similar luminosity studied at sub-millimetre wavelengths (Matrà et al. 2018). The deconvolved images and the modelling also revealed the disc to be (moderately) broad, from an inner edge of ~ 40 au to an outer edge of ~105 au.

A marginal brightness asymmetry was observed with the 70 μm sources after deconvolution, where a greater flux density was measured for the ansa SE of HD 48782. A brightness asymmetry was also observed in the 850 μm source but this time on the NW side of HD 48682. This could suggest an pericentre glow (e.g. Wyatt et al. 1999) at far-infrared wavelengths and a apocentre glow (e.g. Pan et al. 2016) at sub-millimetre wavelengths, similar to what was revealed in the Fomalhaut system (MacGregor et al. 2017), corresponding to a possible eccentricity of about ~ 0.2. This could suggest dust segregation due to grain size perturbed by an unseen companion, however, we do caution that due to the low signal-to-noise of the data, this could be attributed to emission from background contamination.

Combining the disc SED with the multi-wavelength, spatially resolved images we fitted a 3D dust continuum model, assuming the disc to be a single annulus around the star, and calculated a minimum grain size of 0.6 ± 0.1 μm, which is substantially smaller than compared with similar systems studied by (Pawellek et al. 2014). The sub-millimetre photometry has enabled us to constrain the grain size distribution with an exponent of 2 (Kurucz 1969). Further imaging of the system in scatter light and millimetre wavelengths will be necessary to differentiate between the possible architectures of HD 48682's broad disc, either with sub-structure similar to HD 107146 (e.g. Marino et al. 2018), or with an extended halo of dust grains similar to HD 61005 (e.g. MacGregor et al. 2018).

6 DATA AVAILABILITY
The datasets were derived from sources in the public domain:
- Herschel Science Archive: http://archives.esac.esa.int/herschel/
- Hipparcos Input catalogue: https://www.cosmos.esa.int/web/hipparcos/input-catalogue
- NASA/IPAC Infrared Science Archive: https://iris.ipac.caltech.edu/
- Gaia Archive: https://gea.esac.esa.int/archive/
- Castelli & Kurucz Atlas: https://archive.stsci.edu/hsps/reference-atlas/esources/ck04models/
- JCMT Science Archive: https://www.eo-observatory.org/jcmt/science/archive/

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Facilities: Herschel, JCMT, SMA, Spitzer.

Software: HYPERION (Robitaille 2011), emcee (Foreman-Mackey et al. 2013), corner (Foreman-Mackey et al. 2016), matplotlib (Hunter 2007).

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