Dust evolution in the circumstellar disc of the unclassified B[e] star HD 50138

J. Varga, T. Gerják, P. Ábrahám, L. Chen, K. Gabányi and Á. Kóspál

1Leiden Observatory, Leiden University, PO Box 9513, NL2300, RA Leiden, the Netherlands
2Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Konkoly Thege Miklós út 15-17., H-1121 Budapest, Hungary
3Department of Astronomy, Eötvös Loránd University, Pázmány Péter sétány 1/A, Budapest, Hungary
4MTA-ELTE Extragalactic Astrophysics Research Group, Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary
5Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
We studied the disc of the unclassified B[e] star HD 50138, in order to explore its structure, and to find indications for the evolutionary status of this system, whether it is a young Herbig Be or a post-main-sequence star. Using high spatial resolution interferometric measurements from MIDI instrument (N-band) on the Very Large Telescope Interferometer, we analysed the disc size, the time-variability of the disc’s thermal emission, and the spectral shape of the 10 µm silicate feature. By fitting simple disc models, we determined the inclination and the mid-infrared size of the disc, confirming earlier results based on a lower number of observations. We searched for mid-infrared temporal variability of different regions of the disc, and concluded that its morphology is not experiencing significant changes over the observed epochs. We characterized the mid-infrared silicate feature by determining the feature amplitude and the 11.3/9.8 µm flux ratio. The latter parameter is a good indicator of the grain size. The shape of the feature suggests the presence of crystalline silicate grains in the disc. The interferometric data revealed a strong radial trend in the mineralogy: while the disc’s innermost region seems to be dominated by forsterite grains, at intermediate radii both forsterite and enstatite may be present. The outer disc may predominantly contain amorphous silicate particles. A comparison of the observed spectral shape with that of a sample of intermediate-mass stars (supergiants, Herbig Ae/Be stars, unclassified B[e] stars) implied that the evolutionary state of HD 50138 cannot be unambiguously decided from mid-IR spectroscopy.

Key words: stars: emission-line, Be – circumstellar matter – stars: individual: HD 50138 – techniques: interferometric

1 INTRODUCTION
B[e] stars are a class of stars with B spectral type, showing forbidden optical emission lines and infrared (IR) excess, which is emitted by circumstellar dust (Allen & Swings 1976). The B[e] phenomenon is still not very well understood, despite a long history of observations. B[e] stars constitute a heterogeneous group regarding stellar evolution, divided into five main subclasses: supergiants, pre-main sequence (Herbig B[e]) stars, compact planetary nebulae, symbiotic stars, and unclassified B[e] stars (Lamers et al. 1998). Currently half of the B[e] stars are unclassified (Borges Fernandes et al. 2011), however, high spatial resolution observations can provide an efficient classification tool for them (Miroshnichenko 2007). A notable feature of unclassified B[e] stars is their high mass loss rates, compared to normal main-sequence stars, which can not be explained by the wind-theory for main-sequence B-type stars (de la Fuente et al. 2015). Originally unclassified B[e] stars were thought to be isolated objects, but recently de la Fuente et al. (2015) reported that these objects can be also found in clusters. They estimated the age of the stars in the range from 3.5 to 6.5 Myr, which is out of the range for both pre- and post-main-sequence origin, as the former phase lasts for ~ 0.1 Myr, and the main-sequence lifetime is 15 – 20 Myr for a 12 M⊙ star.
They suggested that a new shell phase could have taken
high-spectral-resolution optical spectra from 1999 and 2007.
analysed the spectroscopic variability of HD 50138 using
months (Pogodin 1997). Borges Fernandes et al. (2009)
strong spectral variability, with time-scales lasting from days
ination, its evolutionary phase is not known. HD 50138 exhibits
B[e] star. Later Lamers et al. (1998) labelled it as an
oducts from the ejected material from the star (Oudmaijer 2012).
more, new models reproducing forbidden emission lines
and observations indicate that B[e] supergiants can also host
circular rings (Kraus 2016; Kraus et al. 2016).
HD 50138 (aka. MWC 158) is a B6-7III-V[e] star
Borges Fernandes et al. 2009), with a mass of 6 – 7 \( M_\odot \)
Borges Fernandes et al. 2009; Ellerbroek et al. 2015), at a
distance of 377 ± 9 pc (Gaia Collaboration et al. 2018;
Bailey-Jones et al. 2018). We adopted this distance value
arther, but a 30 day period can be detected in the radial
found only modest signatures for regular short term vari-
ability, but a 30 day period can be detected in the radial
velocity measurements of Merrill (1931). Such a period can
be consistent with the orbital period of a binary system with
mass transfer between the components.
The binarity of HD 50138 has been hypothesized by sev-
eral authors. Baines et al. (2006) used spectro-astrometry to
detect binary companions in a sample of intermediate-mass
stars. They stated that the observed spectral signatures of
HD 50138 are consistent with binarity. The separation of the
companion is estimated to be in the range from 0.5″ to 3″.
Near-IR interferometric observations also indicate asymme-
tries in the distribution of the circumstellar material, which
can also be explained with the presence of a companion
(Ellerbroek et al. 2015; Lazareff et al. 2017; Koutoulaki et al.
2018).

More recently, IR interferometry proved to be a power-
ful tool to reveal the structure of the circumstellar envi-
enment of B[e] stars (Borges Fernandes 2010). The existence
of the circumstellar disc of HD 50138 has been directly con-
firmed by high resolution near- and mid-IR interferometric
observations (Borges Fernandes et al. 2011). If the star is
a post-main-sequence object, then the disc is likely formed
by decretion or as a result of binary interaction (Ellerbroek
et al. 2015). Borges Fernandes et al. (2011) specified the
geometrical parameters of the disc using near- and mid-
IR interferometric observations from the VLTI/AMBER,
VLTI/MIDI and the Keck segment-tilting experiment. They
Got \( i = 56 ± 4° \) for the inclination and \( \theta = 71 ± 7° \) for the
position angle of the disc. Ellerbroek et al. (2015) observed the
Bry line with VLTI/AMBER. They were able to re-
solve the disc, and found that the line emitting region is
smaller (< 2.3 au, adopting the new Gaia DR2 distance),
than the continuum emitting region. This is expected, as
the line emission comes from the inner few au region, which
is too hot for dust to exist.

Kluska et al. (2016) monitored HD 50138 with
VLTI/PIONIER in H band over three epochs. They found
that the morphology of the circumstellar environment is
asymmetric, and varies over weekly or daily time scales.
They explained this variability with a model which includes
a disc and a bright spot which moves around the central star.
Fitting the data with a circular trajectory they got 5.2 mas
(= 1.96 au, adopting the new Gaia DR2 distance) for the ra-
dius, and \( P = 88 \) days for the orbital period. The orientation
and inclination of the fitted orbit is in agreement with the
results of Borges Fernandes et al. (2011). The fit is not good
enough to confirm the existence of a companion. They found
likely that the bright spot is actually a disc asymmetry,
which could be caused by spiral arms or other disc features.
Lazareff et al. (2017) observed HD 50138 as a member of
a large sample of Herbig Ae/Be discs in the H band using
VLTI/PIONIER. They fitted models to the data to deter-
mine the geometry of the inner disc. They found 68 – 72° for
the position angle and 56 – 58° for the inclination, which is
in excellent agreement with the results of Borges Fernandes
et al. (2011) from mid-IR data. They also noted that disc
asymmetry is indicated by the closure phases. Most recently,
Koutoulaki et al. (2018) presented an interferometric study
with VLTI/AMBER, revealing that the circumstellar envi-
enment is complex. They estimated a size of 0.7 – 1.1 au for
the continuum emitting region, and ~0.4 au for the H1 emitting
region\(^1\). They also found, in agreement with the results of
Ellerbroek et al. (2015), that the Bry line-emitting gas is
located in a Keplerian rotating disc. These authors noted
that the observations indicate asymmetric disc structure, or
maybe the presence of a companion. Although these IR in-
ferometric studies revealed much of the rich structure of
the circumstellar environment of HD 50138, they were un-
able to draw conclusions of the evolutionary state. Most au-

\(^1\) Here we also recalculated the sizes using the recent Gaia DR2
distance measurement.
Dust evolution in the disc of HD 50138

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

The Mid-infrared Interferometric Instrument (MIDI, Leinert et al. 2003) was mounted on the Very Large Telescope Interferometer at ESO’s Paranal Observatory, Chile. It was an interferometer, combining the light of either two 8.2 m Unit Telescopes (UTs) or two movable 1.8 m Auxiliary Telescopes (ATs). MIDI worked in the 7.5 to 13 µm spectral range, with $R \approx 30$ (prism), or $R \approx 230$ (grism) spectral resolution.

Earlier MIDI observations of HD 50138 from 2007/08 and 2008/09 were already published by Borges Fernandes et al. (2011). We obtained additional new data in 2014/2015 under our ESO program 094.C-0629(B) (PI: P. Ábrahám). The purpose of these measurements was to monitor the possible variability of the source. All, earlier or new, observations were taken with ATs using the prism as the dispersing element. The distribution of the observations in the $uv$-plane are shown in Fig. 1. Projected baseline lengths ($B_p$) range from 9.7 m to 79.8 m. The position angles ($\phi_B$) of the baselines are nearly evenly distributed.

2.2 Data reduction

We evaluated both the old and our new data, downloaded from the ESO public archive. The raw data are processed by the Expert Work Station (EWS) software (Chesneau 2007; Kühler & Jaffe 2008). Following Menu et al. (2015), the calibration of the target was performed on a nightly basis by determining a transfer function. Instead of taking the closest calibrator observation to determine the value of the transfer function, we perform a linear interpolation in time, by using different calibrators observed the same night (Table 1). Since the transfer function is a time-dependent quantity, the advantage of our strategy is to correct for this time dependency. The transfer function includes the instrumental and sky responses. Then the total and the interferometric (correlated) spectra were calibrated separately. The final data products consist of the total spectra, correlated spectra, spectrally resolved visibilities and differential phases, all in the 7.5 – 13 µm spectral range. The uncertainties of the final spectra are dominated by systematic calibration errors of 10–20 per cent. The uncertainty of the correlated spectra are considerably smaller than that of the total spectra, because the background can be more efficiently subtracted from the interferometric measurements (for more details, see Menu et al. 2015). The 9.4 – 10 µm wavelength range is affected by atmospheric ozone absorption, which makes the total spectrum calibration even more problematic. Thus, we do not use total spectrum data from this range in our analysis. The corresponding parts of correlated spectra, due to the more efficient background removal, are less affected by the ozone..

Lee et al. (2016) studied eight isolated B[e] stars, including HD 50138. They argued that HD 50138 is a post-main-sequence star on the basis, that it is not associated with any known star forming region. They observed HD 50138 with the Submillimeter Array (SMA) at 1.3 mm, and it was unresolved with an angular resolution of ~1″ (~400 au). The steep fall-off of the spectral energy distribution at submillimetre wavelengths indicates a lack of cold grains, thus more compact distribution of dusty circumstellar material than that in typical Herbig stars.

Borges Fernandes et al. (2011) noted that the shape of the 10 µm spectral feature of HD 50138 indicates crystalline silicate grains (e.g., ortho-ensatite), but they did not make a detailed analysis. Mid-IR variability (including spectral variability and possible changes in the disc density and thermal structure) have also remained unexplored. Mid-IR interferometry may also provide clues for the existence of the putative binary companion.

In this paper we aim to address these questions by studying the circumstellar disc of HD 50138 with high spatial resolution mid-IR observations obtained with the VLTI/MIDI, presenting the first spatially resolved analysis of the mid-IR silicate spectral feature. The structure of the paper is as follows: In Sect. 2 we describe the observations and the data reduction. In Sect. 3 we present the results of our interferometric analysis on the disc geometry, check for variability, examine the mid-IR interferometric spectra, and search for signatures of binarity. In Sect. 4 we analyse the properties of the circumstellar dust, and discuss if the new results could shed light on the evolutionary status of this enigmatic source. Finally, in Sect. 5 we summarize our results.
Table 1. Overview of VLTI/MIDI interferometric observations of HD 50138, used in our analysis. $B_p$ is the projected baseline length, $\phi_B$ is the projected position angle of the baseline (measured from North through East), and $\varphi$ is the angular diameter of the calibrator star. $\phi_B$ has a $180^\circ$ ambiguity. We use a convention where $\phi_B$ is confined to the $(-90^\circ, 90^\circ]$ range.

| Date and time (UTC) | Configuration | $B_p$ (m) | $\phi_B$ (°) | Name | $\varphi$ (mas) | Time (UTC) | Comment |
|----------------------|---------------|-----------|--------------|------|-----------------|------------|---------|
| 2007-12-09T03:19:59  | G1H0          | 68.9      | -12.2        | HD 4128 | 5.19          | 02:25      |         |
|                      |               |           |              | HD 48915 | 6.09          | 04:32      |         |
| 2007-12-09T03:40:03  | G1H0          | 68.5      | -10.2        | HD 4128 | 5.19          | 02:25      |         |
|                      |               |           |              | HD 48915 | 6.09          | 04:32      |         |
| 2007-12-12T05:09:38  | G1D0          | 71.5      | -50.0        | HD 29139 | 20.40         | 02:35      |         |
|                      |               |           |              | HD 4128 | 5.19          | 03:30      |         |
|                      |               |           |              | HD 48915 | 6.09          | 04:47      |         |
| 2007-12-12 06:00:52  | G1H0          | 68.1      | 6.9          | HD 29139 | 20.40         | 02:35      |         |
|                      |               |           |              | HD 4128 | 5.19          | 03:39      |         |
|                      |               |           |              | HD 48915 | 6.09          | 04:47      |         |
| 2007-12-13 03:10:16  | G1D0          | 66.6      | -50.1        | HD 29139 | 20.40         | 02:35      |         |
|                      |               |           |              | HD 48915 | 6.09          | 03:31      |         |
| 2007-12-26 07:45:05  | G1D0          | 58.1      | -28.7        | HD 48915 | 6.09          | 07:03      |         |
| 2008-11-10 05:43:04  | E0H0          | 36.7      | 60.4         | HD 48915 | 6.09          | 05:18      | no measured total spectrum |
| 2008-11-10 05:47:01  | E0H0          | 37.1      | 61.0         | HD 48915 | 6.09          | 05:18      | bad quality total spectrum |
| 2008-12-27 06:35:44  | E0G0          | 15.5      | 74.0         | HD 18884 | 12.27         | 02:57      |         |
|                      |               |           |              | HD 48915 | 6.09          | 06:16      |         |
| 2008-12-28 01:39:38  | E0G0          | 10.0      | 50.8         | HD 12929 | 6.90          | 00:36      |         |
|                      |               |           |              | HD 48915 | 6.09          | 02:01      |         |
|                      |               |           |              | HD 48915 | 6.09          | 02:23      |         |
|                      |               |           |              | HD 48915 | 6.09          | 02:46      |         |
| 2008-12-28 02:36:43  | E0H0          | 36.9      | 60.8         | HD 12929 | 6.90          | 00:36      |         |
|                      |               |           |              | HD 48915 | 6.09          | 02:01      |         |
|                      |               |           |              | HD 48915 | 6.09          | 02:23      |         |
|                      |               |           |              | HD 48915 | 6.09          | 02:56      |         |
| 2008-12-30T01:35:48  | H0G0          | 20.3      | 51.7         | HD 12929 | 6.90          | 00:22      |         |
|                      |               |           |              | HD 48915 | 6.09          | 00:56      |         |
|                      |               |           |              | HD 48915 | 6.09          | 00:59      |         |
|                      |               |           |              | HD 48915 | 6.09          | 01:18      |         |
| 2009-01-21T06:01:07  | H0G0          | 27.6      | 74.1         | HD 31398 | 7.07          | 00:23      | no measured total spectrum |
|                      |               |           |              | HD 31398 | 7.07          | 00:37      |         |
|                      |               |           |              | HD 31398 | 7.07          | 00:48      |         |
|                      |               |           |              | HD 31398 | 7.07          | 01:29      |         |
|                      |               |           |              | HD 48329 | 4.62          | 02:22      |         |
|                      |               |           |              | HD 48329 | 4.62          | 02:58      |         |
| 2009-01-21T06:08:39  | H0G0          | 27.1      | 74.0         | HD 31398 | 7.07          | 00:23      | bad quality total spectrum |
|                      |               |           |              | HD 31398 | 7.07          | 00:37      |         |
|                      |               |           |              | HD 31398 | 7.07          | 01:29      |         |
|                      |               |           |              | HD 48329 | 4.62          | 02:22      |         |
|                      |               |           |              | HD 48329 | 4.62          | 02:58      |         |
| 2009-03-08T01:22:53  | E0H0          | 47.6      | 73.4         | HD 12929 | 6.90          | 00:09      |         |
|                      |               |           |              | HD 48915 | 6.09          | 01:41      |         |
| 2014-10-14T06:31:05  | C1A1          | 9.7       | 49.5         | HD 48915 | 6.09          | 05:56      | no measured total spectrum |
|                      |               |           |              | HD 32887 | 6.08          | 07:14      |         |
|                      |               |           |              | HD 32887 | 6.08          | 07:48      |         |
| 2014-10-19T09:04:04  | G1A1          | 79.8      | -74.1        | HD 54605 | 3.60          | 08:48      |         |
| 2014-11-15T04:52:53  | G1A1          | 62.5      | -74.8        | HD 54605 | 3.60          | 04:33      | bad quality total spectrum |
| 2014-11-17T03:57:34  | G1I1          | 36.4      | 5.4          | HD 54605 | 3.60          | 04:10      |         |
| 2014-12-02T03:01:56  | G1I1          | 36.5      | 6.1          | HD 12929 | 6.90          | 02:19      |         |
|                      |               |           |              | HD 48915 | 6.09          | 03:48      |         |
|                      |               |           |              | HD 54605 | 3.60          | 03:20      |         |
| 2014-12-02T04:02:18  | G1A1          | 65.8      | -75.1        | HD 12929 | 6.90          | 02:19      | no measured total spectrum |
|                      |               |           |              | HD 48915 | 6.09          | 03:48      |         |
|                      |               |           |              | HD 54605 | 3.60          | 03:20      |         |
Table 1 – continued

| Date and time (UTC) | Configuration | \( B_p \) (m) | \( \phi_B (\degree) \) | Name \( \varphi \) (mas) | Time (UTC) | Comment |
|---------------------|---------------|---------------|----------------|----------------|------------|---------|
| 2014-12-02T04:19:41 | G1A1          | 68.9          | -75.3          | HD 12929       | 6.90       | 02:19   | only total spectrum |
| HD 48915            | 6.09          |               |                |                | 03:48      |         |                     |
| HD 54605            | 3.60          |               |                |                | 03:20      |         |                     |
| 2014-12-10T02:54:38 | G1I1          | 36.9          | 11.5           | HD 54605       | 3.60       | 02:40   |                     |
| 2015-01-09T04:56:11 | G1I1          | 46.3          | 43.7           | HD 48915       | 6.09       | 04:23   |                     |
| HD 54605            | 3.60          |               |                |                | 04:40      |         |                     |

Dust evolution in the disc of HD 50138

3 RESULTS

3.1 Geometric modelling

Interferometric observations can be used to characterize the geometry of circumstellar discs. Monnier et al. (2009) and Borges Fernandes et al. (2011) have already determined the basic properties of the disc of HD 50138 at mid-IR wavelengths. They used various geometric models to determine the size, the inclination, and the position angle (\( \phi \)) of the major axis. In the following, adding our new data from 2014/15, we re-evaluate the system morphology. First we use a simple Gaussian brightness distribution model to determine the orientation of the disc. Then we apply a semi-physical interferometric model to determine the size of the mid-IR emitting region and look for signs of variability.

For every observation we determined a characteristic size of the disc, defined as the half width half maximum (HWHM) of a Gaussian brightness distribution fitted to the visibilities, according to the following formula:

\[
\sigma = \frac{\sqrt{\ln 2}}{\pi} \frac{\sqrt{-\ln V}}{B_p/\lambda},
\]

where \( \lambda \) is the wavelength, in this case \( \lambda = 10.7 \) \( \mu \)m, \( V \) is the visibility at the selected wavelength, and \( B_p \) is the projected baseline length.

The results are shown in Fig. 2. We get sizes to different position angles. This enables us to measure the inclination of the disc. Therefore we fitted an ellipse to the resulting Gaussian sizes taking into account uncertainties with inverse squared error weighting. The fitted ellipse is plotted on Fig. 2. From the plot it can be seen, that the data points from 2007 are close to the minor-axis of the projected image of the disc, and the data from 2008-2009 are aligned with the major-axis. Our new measurements, however, are at intermediate position angles. Disc inclination (\( i \)) is calculated simply by \( i = \arccos \frac{b}{a} \), where \( b \) and \( a \) are the fitted semi-minor and semi-major axes, respectively. The resulting inclination is \( 56.6^\circ \pm 2.3^\circ \), and the position angle (\( \phi \)) of the major axis is \( 63.4^\circ \pm 3.4^\circ \) (measured from north to east), in agreement with the results of Borges Fernandes et al. (2011), although they used different interferometric models to fit the data. One of their models, which provided the best results, contained two elliptical Gaussian distributions, representing a compact and an extended component. The semi-major axis of the fitted ellipse in our fit, i.e. the half-light radius (HWHM of the Gaussian model) of the disc is \( 8.3 \pm 0.3 \) au (\( 21.9 \pm 0.8 \) mas).

Pre-main sequence Herbig Ae/Be and T Tauri stars are known about their inherent brightness variability. The changing emission of the young star affects the irradiation of its disc, and the disc may show variability in its IR thermal emission, too. In order to outline any IR variability of HD
In our model we assume that the disc radiates as a blackbody:

\[ I_\nu (r) = \tau_\nu B_\nu (T(r)), \]

where \( I_\nu \) is the wavelength dependent intensity, \( \tau_\nu \) is the opacity, \( B_\nu \) is the Planck-function, and \( T \) is the temperature. The dependency of the temperature on the radius \( r \) is a power-law:

\[ T(r) = T_{\text{in}} \left( \frac{r}{R_{\text{in}}} \right)^{-q}, \]

where \( R_{\text{in}} \) is the inner radius, \( T_{\text{in}} \) is the temperature at \( R_{\text{in}} \), and \( q \) defines the temperature gradient. Following Menu et al. (2015), we derive the relation between \( R_{\text{in}} \) and \( T_{\text{in}} \) as

\[ R_{\text{in}} = \left( \frac{L_*}{4\pi\sigma T_{\text{in}}^4} \right)^{1/2}, \]

where \( L_* \) is the luminosity of the star. For \( L_* \) we use the value by Ellerbroek et al. (2015), but recalculating it for the new Gaia DR2 distance measurement: \( L_* = (680 \pm 230) L_\odot \). The outer radius is fixed at 300 au where the mid-IR emission is negligible. The total flux density, which is the integrated emission of the source over the whole disc \( (F_{\text{tot,}\nu}) \), and the correlated flux density \( (F_{\text{corr,}\nu}) \) are derived from the following formulas:

\[ F_{\text{tot,}\nu} = \int_{R_{\text{in}}}^{R_{\text{out}}} 2\pi r \tau_\nu B_\nu (T(r)) \, dr. \]

\[ F_{\text{corr,}\nu} (B_{\text{eff}}) = \frac{\int_{R_{\text{in}}}^{R_{\text{out}}} r B_\nu (T(r)) J_0 (2\pi r B_{\text{eff}} / (4d)) \, dr}{\int_{R_{\text{in}}}^{R_{\text{out}}} r B_\nu (T(r)) \, dr}. \]

where \( J_0 \) is the zero-order Bessel-function, and \( d \) is the distance of the star. The half-light-radius \( (R_{\text{hl}}) \) of the disc is defined as the radius at which the integrated intensity is half of the total flux density:

\[ \frac{F_{\text{tot,}\nu}}{2} = \int_{R_{\text{in}}}^{R_{\text{hl}}} 2\pi r I_\nu (r) \, dr. \]
interferometric measurements (Sect. 2.2). In the fitting process we varied two free parameters, \( q \) and \( R_{\text{in}} \). The best-fit parameters are computed in a grid, by maximizing the log-likelihood. Table 2 presents the results for five selected wavelengths.

We have got 2.7 – 3.7 au (7.2 – 9.9 mas) for the inner radius, with an increasing trend with wavelength. We can compare this result with the dust sublimation radius \( (R_{\text{sub}}) \), which can be computed from Eq. 8, by substituting \( T_{\text{in}} = T_{\text{sub}} = 1500 \) K for the sublimation temperature (Dullemond & Monnier 2010). The corresponding sublimation radius is 1.8 ± 0.3 au (4.7 ± 0.8 mas). This is smaller than the observed inner radius, suggesting the presence of a hole in the dust disc. For a certain inner radius we can compute an equilibrium temperature using Eq. 8. The equilibrium temperatures at the inner disc edge are in the range of 1050 – 1200 K. The mid-IR measurements trace the distribution of the dust. However, the detected hole is not empty, as gas was detected within this radius (Ellerbroek et al. 2015; Koutoulaki et al. 2018). This is the first detection of an inner dusty disc hole (which is larger than the sublimation radius) in the dusty disc of a B[e] star to our knowledge. We note, however, that combined multi-wavelength data-sets are needed to unambiguously determine the exact parameters of the inner dusty disc hole (as an example, we refer to Menu et al. 2014).

Similar inner disc gaps are frequently observed in young intermediate-mass systems, in particular in transitional discs (Espaillat et al. 2014), but were also detected with MIDI around other Herbig Ae/Be stars (Menu et al. 2015). There are several clear mechanisms proposed, like grain growth, photoevaporation, and dynamical clearing by a (sub-)stellar companion (Espaillat et al. 2014). Khushka et al. (2016) reported a moving asymmetry in the disc of HD 50138, which could be fitted with a circular trajectory with a radius of ∼2 au. However, they could not directly link the asymmetry to the presence of a companion, rather they hypothesized that it may be a spiral arm or other disc asymmetry. We note that spiral arms in circumstellar discs can be induced by companions or planets (e.g., Bae & Zhu 2018; Boehler et al. 2018; Dong et al. 2018; Müller et al. 2018; Wagner et al. 2018). Such a scenario can be compatible with the observed features of the disc around HD 50138.

Near-IR interferometric observations of HD 50138 (e.g., Lazareff et al. 2017; Koutoulaki et al. 2018) yielded a smaller size (0.7 – 1.1 au) for the continuum-emitting region. Such deviations can result from the existence of an additional continuum-emitting component inside the sublimation radius, usually attributed to refractory dust or to hot gas by some authors (e.g., Benisty et al. 2010). Alternatively, an optically thick inner disc applied to disc models of Be stars, similar to the pseudo-photospheres in luminous blue variables, can also provide an explanation (Vieira et al. 2015). The nature of this component however, is not very well constrained.

From our model we determine a range of 8.2 – 9.5 au (21.9 – 25.1 mas) for the half-light radius as a function of wavelength. We found that the half-light radius at wavelengths corresponding to the continuum \( (R_{h} = 8.2 – 8.6 \text{ au}) \) is smaller than at wavelengths corresponding to the silicate feature \( (R_{h} = 9.2 – 9.5 \text{ au}) \). This means that the optically thick continuum is confined to a smaller area than the optically thin silicate emission.

We checked the residual distribution of the data points around the best fit model line in Fig. 3. We mark the epochs of the observations with colour. In the 25 m < \( B_{\text{eff}} < 40 \) m range some data points are significantly above the model, possibly indicating fine structures not accounted by our simple geometry. However, we found no trend in the residuals with time, thus excluding any significant variability in the mid-IR morphology of the disc over the observed seven year time range. Possible variations in the total flux data will be discussed in Sect. 4.2.

3.2 The 10 \( \mu \)m silicate feature

There are several notable spectral features observable in circumstellar discs in the N-band, such as the features of silica, various silicates, and polycyclic aromatic hydrocarbons (PAHs). The MIDI spectra of HD 50138 have sufficient spectral resolution \( (R \approx 30) \) and signal-to-noise ratio to study these features. The interferometric observations enable us to study any spatial variability in the spectra. With our time coverage of 7 years, we can also look for potential temporal changes in the spectra.

We sorted the observed correlated spectra into several groups, based on their inclination-corrected angular resolution, calculated from the effective baseline lengths. Angular resolution is measured as the half width at half maximum (HWHM) of a fringe. We defined three bins in resolution, corresponding to different regions of the disc: 3 – 8 au \( (8 – 21 \text{ mas, innermost disc}) \), 8 – 14 au \( (21 – 37 \text{ mas, inner disc}) \), and ∼23 au \( (∼61 \text{ mas, intermediate disc}) \). As a fourth bin, we included the total spectra, which contain emission from the full disc. Since within the individual groups there was no obvious dependence of the spectral shape on the
position angle, we averaged the spectra in each bin. The resulting spectra correspond to all integrated emission within a given disc radius determined by the resolution. The results are plotted in the left panel of Fig. 4. In order to explore the differences among the radial disc regions, in the right panel of Fig. 4 we present differential spectra between the averaged spectra, which represent emission of ring-shaped regions in the disc.

The averaged spectra, both the total and correlated ones, exhibit a broad emission feature at 10 $\mu$m, characteristic of the emission of small silicate grains. The correlated spectra show clear edges in the spectral feature at 9.2 and 11.3 $\mu$m. These turning points seem also to be present in the noisier total spectra. The profiles, however, show significant variations in how strong are these turning points. The innermost disc spectrum ($r < 8$ au) is relatively flat, nevertheless it exhibits a definite change in its slope at 11.3 $\mu$m. While the intermediate regions show both edges with a characteristic plateau between 9.2 and 11.3 $\mu$m. The 11.3 $\mu$m edge in the total disc spectrum is less conspicuous. The amplitude of the feature gets smaller in the inner and innermost disc regions.

**Figure 4.** Averaged spectra of various radial disc regions, derived from the correlated and total spectra. Left: integrated emission within given radii. Right: differential spectra from ring-shaped regions.

## 3.3 Binarity

Following previous near-IR interferometric studies that observed disc asymmetries (e.g., Kluska et al. 2016; Koutoulaki et al. 2018), we examined the MIDI data to find indications for binarity. The binary signal in the spectrally resolved correlated spectra and differential phases usually appears as a sinusoidal modulation. Some of the highest resolution correlated spectra of HD 50138 show patterns, which might be interpreted as a binary modulation. In Fig. 5 we show three spectra of this kind (top panel). As the correlated spectra also exhibit silicate emission, it is difficult to disentangle the potential sinusoidal binary signal from the spectral feature. A companion or an asymmetric disc structure would also cause a modulation in the differential phases, plotted on the bottom panel. The differential phase curves show some deviations from the flat zero degree line, but the signal is generally too weak and noisy to be able to confirm binarity or more generally an asymmetric disc structure. MIDI is sensitive to binaries with separations larger than $\sim 50$ mas, with mid-IR flux ratios larger than $\sim 0.1$ (Varga et al. 2018). Since we do not see clear indication for binarity from these data, the companion is either closer to the star than this limit, or is too faint in mid-IR, or both. Furthermore, the possibility that there is no companion cannot be discarded.
4 DISCUSSION

4.1 Dust properties

Cosmic dust grains are predominantly formed in the stellar wind of AGB stars, then distributed in the interstellar space. Miroshnichenko (2007) discusses the origins of dust around different classes of B[e] stars: Two groups can be defined regarding the dust formation time, one is where the formation happened during earlier evolutionary phases, the other is where recent or ongoing dust formation can be observed. Herbig B[e] stars, where the dust has an interstellar origin (i.e. it is produced by previous generations of stars), and compact planetary nebulae B[e]-type stars, where the dust is left over from the previous AGB state, are examples for the first case. All other classes, i.e. symbiotic, supergiant, and unclassified B[e] stars have freshly produced dust around them. In the latter two classes the companion is possibly responsible for the mass loss, and the dust is formed in a dense radiation-driven stellar wind, where self-shielded parts (from UV radiation) are the cradles for dust condensation. Miroshnichenko (2007) also suggests that the dust in unclassified B[e] stars should form around the binary, as a consequence of a recent or ongoing rapid mass transfer phase. However, the same author claims that only 30% of unclassified B[e] stars are suspected or recognized binaries. Thus, a single star scenario with dust formation in the circumstellar disc cannot be discarded. de la Fuente et al. (2015) presented an alternative hypothesis, that a stellar merger can also explain the formation of large amounts of circumstellar dust, thus unclassified B[e] stars could be the products of a recent merger. From the observational side, Miroshnichenko et al. (2011) studied the mid-IR spectra of 25 unclassified B[e] stars, and they detected silicate emission features in most observed objects, and PAH emission in some.

Discs around Herbig B[e] stars are formed by the collapse of the protostellar cloud, which contains interstellar dust. The majority of these grains are small, sub-micron sized amorphous silicate particles (Kemper et al. 2004). In circumstellar discs, however, grains can be reprocessed through crystallization and grain growth. There are several crystal formation mechanisms, like thermal annealing in the inner disc above a temperature of ~1000 K; re-condensation after evaporation; or heating by shock waves (Fabian et al. 2000; Harker & Desch 2002; Gail 2004). Gail & Sedlmayr (1999) found that crystalline olivine can even directly condense out from the stellar wind of oxygen-rich mass-losing stars. Crystalline grains are found throughout the discs, indicating that if crystalline dust formed close to the star, it had to be transported to the outer disc. Radial transport mechanisms, such as disc/stellar winds are proposed for protoplanetary discs (e.g., Gail 2001, 2004). Alternatively, shock waves due to gravitational instabilities, or episodic outbursts can induce crystal formation at a greater distance from the central source.

Our MIDI spectra exhibit characteristic silicate emission profiles, with two conspicuous edges at 9.2 and 11.3 μm, and with a variety of the relative strength of the feature above the continuum (Sect. 3.2, Fig. 4). Such features may imply the presence of crystalline silicates of different types, but may also be related to grain growth (van Boekel et al. 2003; Przygodda et al. 2003). Additionally, the replenishment of dust at the disc surface by large grains, coming from the midplane or inner regions, may also take place here (e.g., Ciesla 2007; Turner et al. 2010). Thus, it is hard to determine the origin of the spectral features unambiguously. In the following, we will try to interpret our MIDI results in different scenarios, and draw conclusions about the radial dust composition of the inner circumstellar disc.

In order to explore if the spectral shape could be due to crystalline silicates, we compare the features present in the spectra of HD 50138 with various laboratory spectra of silicate dust grains from van Boekel et al. (2005) (Fig. 7 therein). To determine the exact dust composition, we would need very high signal-noise ratio (Juhász et al. 2010). The MIDI spectra are less adequate for such analysis, nevertheless we can decide whether amorphous or crystalline dust is the dominant component, and we can identify the most likely mineral types. Fig. 7 of van Boekel et al. (2005) suggests that the shoulders at 11.3 μm may be attributed to crystalline forsterite particles. While PAHs may also exhibit a peak at this wavelength, the fact that the feature is present in the correlated spectra makes a PAH interpretation unlikely. The emission of these carbonaceous particles is expected to be distributed smoothly over a very large spatial region, due to their transient heating (Allamandola et al. 1985), compared to the more compact 10 μm silicate emission. Thus, it would be mostly filtered out by the interferometer, as such large structures become fully resolved at the baselines we used. Consequently the interferometric signal of the PAHs is very low at usual VLTI configurations, compared to the warm, silicate emitting circumstellar material. PAH features could be seen in the MIDI total spectra, but we find no indication for it in the case of HD 50138. In the correlated spectra we see a shoulder around 9.2 μm. This wavelength is somewhat shorter than that of the strong forsterite peak at ~10 μm, thus we propose that the 9.2 μm feature in our spectra is more likely to be either enstatite or silica (see Fig. 7 from van Boekel et al. 2005). A contribution from small amorphous particles would follow a sharp, triangular shape emission feature peaked at about 9.8 μm, which may contribute to the outer disc spectrum.

In the framework of the crystalline scenario, one would conclude that the innermost part of the HD 50138 disc (within 8 au) is mainly populated by forsterite grains, while at intermediate radii (8 ~ 23 au) also enstatite appears with comparable amplitude. This radial distribution might suggest that in the innermost disc the temperature is too high for enstatite, although from our modelling we expect T ≈ 600 K at 8 au, indicating that both species can exist in the < 8 au region (for dust condensation temperatures we refer to Grossman 1972 and Tielens 1990). Maybe the fraction of enstatite in the innermost region is too low to detect it in the MIDI spectra. The outer part of the disc (r > 23 au) lacks the 11.3 μm edge, but exhibits a broad peak between 8 and 9 μm. The shape of this feature does not well match with the templates of van Boekel et al. (2005), but it may correspond to silica or small amorphous (pyroxene) particles. Considering, however, the relatively large radii, and that crystallization mostly take place in the hot inner disc, the latter explanation is more appealing. A similar trend, that the level of crystallinity is higher toward the centre and lower in the outer disc was observed by van Boekel et al. (2004).

In the presence of a population of larger, micrometer-sized silicate grains, the profile of the 10 μm peak will ex-
inhibit a characteristic trapezoidal shape (Bouwman et al. 2003). Studying a sample of young intermediate-mass Herbig Ae/Be stars, van Boekel et al. (2003) found a linear relationship between the ratio of the 11.3 to the 9.8 μm fluxes of the continuum-subtracted spectra and the strength of the silicate feature (Fig. 6). The authors interpreted this relationship as evidence for the removal of small (∼0.1 μm) grains from the disc surface while large (1–2 μm) grains remain, and for the increased presence of crystalline silicates. In HD 50138 the spectral shapes at intermediate disc radii (8 < r < 23 au) are trapezoidal. In order to check whether these spectra could be interpreted in terms of grain growth, following van Boekel et al. (2003) we computed the normalized spectra with the following formula:

\[ F_{\nu, \text{norm}} = \frac{(F_{\nu} - F_{\nu, \text{cont}})}{(F_{\nu, \text{cont}})} + 1 \]  

where \( F_{\nu, \text{norm}} \) is the wavelength dependent normalized flux, \( F_{\nu} \) is the flux, and \( F_{\nu, \text{cont}} \) is the continuum which we determined from a linear fit to the data points between 7.5 and 8.0 μm and between 12.5 and 13 μm. The strength of the feature is then determined as the maximum of \( F_{\nu, \text{norm}} \). The flux ratio is derived from the continuum-subtracted spectra. The results, computed for the different ring-shaped disc regions of Fig. 4, are overplotted in Fig. 6. In case of the outer disc spectrum (r > 23 au) we could not get a reliable estimation, because of the large uncertainty of the linear continuum fit. Thus we do not show the corresponding data point in the figure. The data points representative of three disc regions outline a trend, that is significantly steeper than the relationship of the Herbig Ae/Be stars. We suggest that the spectral shapes in HD 50138 are more consistent with the presence of crystalline grains in the disc than with grain growth.

Now we try to characterize the expected differences between the dust content of pre-main-sequence B[e] and unclassified B[e] stars in order to shed light on the origin of dust around HD 50138. In pre-main-sequence stars the dust mainly originates from an existing interstellar cloud, while in unclassified B[e] stars it is supposed to form in situ around the star, in an inside-out fashion. This should result in observable differences between these classes. Therefore the dusty discs around older B[e] stars are expected to be compact, and the freshly condensed dust grains should be very small (Lee et al. 2016). In the case of HD 50138 we showed that the mid-IR emitting region has a size of \( R_{\text{hl}} \approx 9 \text{ au} \). We can compare this size to the results of Menu et al. (2015), who studied the size distribution of discs around pre-main-sequence stars. We find that the mid-IR size of HD 50138 is similar to the size of discs around Herbig Be stars with similar luminosities (which are in the range of \( \sim 3–10 \text{ au} \)). We note, however, that a really compact appearance for older B[e] stars is expected at longer wavelengths, due to the lack of cold dust in these systems. Lee et al. (2016) found that the fall-off of the SEDs of HD 50138 and HD 45677 toward submillimeter wavelengths suggests a lack of cold grains, thus more compact dusty envelopes than those around Herbig stars. Sandell et al. (2018) confirmed that there is very little cold dust in the disc of HD 50138. Furthermore, they found that \(^{13}\)CO in the disc is enriched by more than a factor of five, which is uncommon for young stellar objects, supporting that HD 50138 is not a Herbig star.

The other expectation for dust around older B[e] stars is the presence of freshly produced grains. In the case of HD 50138 we clearly see the signs of dust evolution, with the more processed dust located closer to the star. This seems to contradict the inside-out dust formation scenario, and a similar trend were observed in discs around pre-main sequence stars (e.g., van Boekel et al. 2004; Varga et al. 2018). This argument might seem to support the interstellar origin of the dust around HD 50138. We note, however, that crystalline silicates are frequently found around evolved stars (AGB stars and red supergiants) (e.g., Waters et al. 1996; Speck et al. 2000; Liu et al. 2017), and many aspects of the dust condensation sequence and crystallization are still unclear. A possible scenario, which was proposed for AGB and red supergiant stars (Waters et al. 1996), is that in dense parts of the stellar wind the dust can stay warm long enough to allow formation of crystals.

### 4.2 Variability

HD 50138, as other B[e] stars, shows permitted and forbidden emission lines in its spectrum, which traces the gas content. The dust is observed by its IR excess and the silicate spectral feature. A notable result of our geometric modelling, that we do not detect significant changes in the structure of the N band emitting disc region (Sect. 3.1). This is different from the results on both the optical spectral line variations (Jeřábková et al. 2016) and the changes in the near-IR morphology of the disc (Kluska et al. 2016). The location of the optical and near-IR variable features is likely the central area of the system, inside \( r < 2 \text{ au} \), which is the radius of the rotating H band asymmetry. From our modelling we find that the N band emitting region begins at \( R_{\text{hl}} \approx 2.7–3.7 \text{ au} \). Thus the more dynamic innermost and less variable outer part of the system may be spatially separated. We note, however, that the temporal coverage of our observations are sparse,
and thus not well suited for variability analysis. Additionally, the time scales we can probe (typically a few weeks to years) are either too long or too short compared to most periods of optical spectral variations (Pogodin 1997; Borges Fernandes et al. 2012; Jěrábková et al. 2016).

Apart from the morphology, we can also look for variations in the total N band flux. We divided our observations into three bins, representing the measurements from 2007, 2008/2009, and 2014/2015. We then calculated a median total spectrum in each bin. We found that the average N band flux was 30 per cent lower in 2007 than later, which indicates real time variability. Comparing this finding with the optical line monitoring of Jěrábková et al. (2016), we do not observe correlations between the long-term trends of the optical and mid-IR variations.

In Fig. 7 we compare the N band flux variations to optical photometric data from the ASAS3 (Pojmanski 1997) and ASAS-SN (Shappee et al. 2014; Jayasinghe et al. 2018) databases. We plot an additional N band data point calculated from a Spitzer Infrared Spectrograph observation from 2004-10-26. The optical measurements by the ASAS3 outline a trend showing a slight dip around the first three N data points. The average magnitude level of the ASAS-SN data is ~ 0.15 mag lower than that of the ASAS3 data, however, the last MIDI flux is still high. Therefore the correlation may not hold for an extended period of time. Borges Fernandes et al. (2012) analysed the optical line profile variability of HD 50138 and also confirmed night-to-night variations. They pointed out that strong short-term changes are linked to the lines formed in the upper layers of the stellar atmosphere, while lines originating in the circumstellar dust are shifted by 11 mag. The MJDs for the MIDI data points are 54447.70, 54851.41, and 57000.90.

**Figure 7.** Optical V band (black symbols) and mid-IR N band (blue and red points) light curves of HD 50138. The mid-IR points are shifted by 11 mag. The MJDs for the MIDI data points are 54447.70, 54851.41, and 57000.90.

**4.3 Evolutionary state**

Despite numerous efforts, the evolutionary state of unclassified B[e] stars is still uncertain. In case of HD 50138 there is a slight preference in the literature for either late main-sequence or post-main sequence state (e.g., Borges Fernandes et al. 2009; Ellerbroek et al. 2015). Borges Fernandes et al. (2012) observed short-term optical line profile variability indicating stellar pulsations similar to pulsating Be stars. They also suggested that the object is at the end, or just evolving off the main sequence. Kluaka et al. (2016) placed the star on the Hertzsprung-Russell diagram, and fitted isochrones for a young and an old scenario. They got ages of 0.3 – 0.5 Myr for the young, and 100 – 200 Myr for the old scenario. Both scenarios are consistent with the observations.

Here we compare our observations of HD 50138 with publicly available spectra of other B[e] stars from the MIDI archive to find possible correlations between the spectral shape and the known evolutionary state in different subgroups. We expect such kind of correlations as the physical conditions for the disc formation and evolution around supergiants and around pre-main sequence stars can be very different. Our sample consists of supergiants, young Herbig Ae/Be stars (including three Herbig Be stars), and unclassified B[e] stars. The MIDI data were consistently reduced and calibrated using the methods described in Sect. 2.2. Looking at the 8 – 13 µm total spectra, we can distinguish two main groups in the sample: one group showing silicate emission, like HD 50138, and another one exhibiting no silicate emission, but showing other small amplitude spectral features. A characteristic shape in the latter group consists of two wide bumps, one between 8 and 9.5 µm, the other between 10 and 13 µm. We tentatively attribute this feature to either silico or to PAH emission (van Boekel et al. 2005). In the group exhibiting silicate emission we find Herbig Be stars, such as HD 100546 and HD 259431, but also a supergiant B[e] star (HD 62623) and unclassified B[e] stars (HD 45677, HD 50138). The trend of the spectral shape with increasing baselines in HD 45677 is very similar to that of HD 50138, indicating similar inner disc structures. The other group, showing no or very weak silicate emission, also consists of Herbig Be (MWC 297), supergiant B[e] (GG Car, CPD-52 9243, CPD-57 2874), and unclassified B[e] stars (MWC 349 A, Hen 3-1191, MWC 300). Consequently, we can make no distinction on the evolutionary state of HD 50138 and other B[e] stars based only on the 8 – 13 µm spectral features. The material composition and structure of the circumstellar dust in these objects seem to be too diverse to be directly linked to the disc evolution. Finally we note that HD 62623 and GG Car are confirmed binaries and CPD-52 9243 may be too (Piets et al. 1995; Marchiano et al. 2012; Cidale et al. 2012), and binarity possibly plays a key role in the B[e] phenomenon.
5 SUMMARY

We have studied the circumstellar disc of the unclassified B[e] star HD 50138 using mid-IR (7.5 − 13 µm) interferometric spectra observed between 2007 and 2015 with the VLTI/MIDI instrument. The main results of our analysis are as follows:

- We determined the orientation of the circumstellar disc from the visibilities at 10.7 µm. The resulting inclination is 56.6°±1.1°, and the position angle is 63.4°±1.5° (measured from north to east), in agreement with previous results.

- We fitted the interferometric data with a geometric disc model adopting ring geometry, and blackbody radiation with a power-law temperature profile. We obtained a power-law temperature profile over the period 2007–2015. However, we found that the half-light radius at wavelengths corresponding to the continuum ($R_{hl} = 8.2 − 8.6$ au) is smaller than at wavelengths corresponding to the silicate feature ($R_{hl} = 9.2 − 9.5$ au). This means that the optically thick continuum is confined to a smaller area than the optically thin silicate emission.

- We analysed the MIDI spectra on different spatial scales. The correlated spectra show a clear feature between 9.2 and 11.3 µm. The amplitude of the feature gets smaller in the inner disc regions.

- The spectra signs of dust evolution. We interpret the observed spectral shapes with two scenarios: (1) crystallization of silicate dust grains (forsterite, enstatite, silica), and (2) grain growth. We suggest that the spectral shapes in HD 50138 are more consistent with the presence of crystalline grains in the disc than with grain growth.

- A novel result is that our interferometric data revealed a strong radial trend in the disc mineralogy: while the innermost region seems to include only forsterite grains, at intermediate radii both forsterite and enstatite are present. The outer disc may predominantly contain amorphous silicate particles.

- Our observations implied no significant temporal variability of the mid-IR disc morphology or the silicate emission profile over the period 2007–2015. However, we found that the average N band total flux was 30 per cent lower in 2007 compared to MIDI and it will measure closure phases in the N band for the first time. This will enable us to investigate possible binarity and disc asymmetries in great detail, with respect to earlier similar studies at near-IR wavelengths (Kluska et al. 2016; Lazareff et al. 2017; Koutoulaki et al. 2018). L and M band spectral coverage of MATISSE can also complement our view on the inner disc structure of HD 50138.

ACKNOWLEDGEMENTS

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 Research and Innovation programme under grant agreement No. 716155 (SACCRED). This work is based on observations made with ESO telescopes at the Paranal Observatory. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. The Combined Atlas of Sources with Spitzer IRS Spectra (CASSIS) is a product of the IRS instrument team, supported by NASA and JPL. KG acknowledges the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. JV and KG acknowledge the Fizeau exchange visitors program which is funded by WP11 of OPTICON/H2020 (2017–2020), grant agreement 730890. We thank the anonymous referee for highly useful comments and suggestions.

REFERENCES

Allamandola L. J., Tielens A. G. G. M., Barker J. R., 1985, ApJ, 290, L25
Allen D. A., Swings J. P., 1976, A&A, 47, 293
Bae J., Zhu Z., 2018, ApJ, 859, 119
Bailer-Jones C. A. L., Rybizki J., Fouesneau M., Mantelet G., Andrae R., 2018, AJ, 156, 58
Baines D., Oudmaijer R. D., Porter J. M., Pozzo M., 2006, MNRAS, 367, 737
Benisty M., et al., 2010, A&A, 511, A74
Berger J. P., Segransan D., 2007, New Astronomy Reviews, 51, 576
Boehler Y., et al., 2018, ApJ, 853, 162
van Boekel R., Waters L. B. F. M., Dominik C., Bouwman J., de Koter A., Dullemond C. P., Paresce F., 2003, A&A, 400, L21
van Boekel R., et al., 2004, Nature, 432, 479
van Boekel R., Min M., Waters L. B. F. M., de Koter A., Dominik C., van den Ancker M. E., Bouwman J., 2005, A&A, 437, 189
Borges Fernandes M., 2010, in Revista Mexicana de Astronomia y Astrofisica Conference Series, pp 98–99
Borges Fernandes M., Kraus M., Chesneau O., Domiciano de Souza A., de Araújo F. X., Stee P., Meilland A., 2009, A&A, 508, 309
Dust evolution in the disc of HD 50138

Borges Fernandes M., et al., 2011, A&A, 528, A20
Borges Fernandes M., Kraus M., Nickeler D. H., De Cat P., Lampens P., Pereira C. B., Oksala M. E., 2012, A&A, 548, A13
Bouwman J., de Koter A., Dominik C., Waters L. B. F. M., 2003, A&A, 401, 577
Chesneau O., 2007, New Astron. Rev., 51, 666
Cidale L. S., et al., 2012, A&A, 548, A72
Ciesla F. J., 2007, ApJ, 654, L159
Dong R., Najita J. R., Brittain S., 2018, ApJ, 862, 103
Dullemond C. P., Monnier J. D., 2010, Annual Review of Astronomy and Astrophysics, 48, 205
Ellerbroek L. E., et al., 2015, A&A, 573, A77
Espaillat C., et al., 2014, in Beuther H., Klessen R. S., Dullemond C. P., Henning T., eds, Protostars and Planets VI. p. 497 (arXiv:1402.7103), doi:10.2458/azu_uapress_9780816531240-ch022
Fabian D., Jäger C., Henning T., Mutschke H., 2000, A&A, 364, 282
de la Fuente D., Najarro F., Trombley C., Davies B., Figer D. F., 2015, A&A, 575, A10
Gaia Collaboration et al., 2018, A&A, 616, A1
Gail H. P., 2001, A&A, 378, 192
Gail H. P., 2004, A&A, 413, 571
Gail H. P., Sedlmayr E., 1999, A&A, 347, 594
Grossman L., 1972, Geochimica et Cosmochimica Acta, 36, 597
Harker D. E., Desch S. J., 2002, ApJ, 565, L109
Jaschek M., Jaschek C., Andrillat Y., 1993, Astronomy and Astrophysics Supplement Series, 97, 781
Jayasinghe T., et al., 2018, arXiv e-prints, p. arXiv:1809.07329
Juhász A., et al., 2010, ApJ, 721, 431
Kemper F., Vriend W. J., Tielens A. G. G. M., 2004, ApJ, 609, 826
Kluska J., Benisty M., Soulez F., Berger J. P., Le Bouquin J. B., Malbet F., Lazareff B., Thiébaut E., Berthoud S., Berger J. P., Le Bouquin J. B., Malbet F., Lazareff B., Thiébaut E., 2016, A&A, 591, A82
Köhler R., Jaffe W., 2008, in Richichi A., Delplancke F., Paresce F., Chelli A., eds, The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation. p. 569, doi:10.1007/978-3-540-74256-2_93
Koutoulaki M., Garcia Lopez R., Natta A., Caratti o Garatti A., Coffey D., Sanchez-Bermudez J., Ray T. P., 2018, A&A, 614, A90
Kraus M., 2016, Boletin de la Asociacion Argentina de Astronomia La Plata Argentina, 58, 70
Lamers H. J. G. L. M., Zickgraf F.-J., de Winter D., Houziaux L., Zorec J., 1998, A&A, 340, 117
Lazareff B., et al., 2017, A&A, 599, A85
Lepoutre E., et al., 2016, in Optical and Infrared Interferometry and Imaging V, p. 99070A, doi:10.1117/12.2233052
Menu J., et al., 2014, A&A, 564, A93
Menu J., van Boekel R., Henning T., Leinert C., Waelkens C., Waters L. B. F. M., 2015, A&A, 581, A107
Merrill P. W., 1931, ApJ, 73, 348
Miroshnichenko A. S., Gray R. O., Bjorkman K. S., Rudy R. J., Lynch D. K., Carciofi A. C., 2011, in Neiner C., Wade G., Meynet G., Peters G., eds, IAU Symposium Vol. 272, Active OB Stars: Structure, Evolution, Mass Loss, and Critical Limits. pp 412–413, doi:10.1017/S1743921311010970
Monnier J. D., Tuthill P. G., Ireland M., Cohen R., Tannirkulam A., Perrin M. D., 2009, ApJ, 700, 491
Müller A., et al., 2018, A&A, 617, L2
Oudmaijer R. D., 2012, in Circumstellar Dynamics at High Resolution. Proceedings of a Joint ESP/Brazilian Workshop held at Foz do Iguaçu, Brazil, 27 February-2 March, 2012. ASP Conference Proceedings, Vol. 464. Edited by A. Carciofi and Th. Rivinius. San Francisco: Astronomical Society of the Pacific, 2012, p. 3, p. 3
Plota H., Waelkens C., Trams N. R., 1995, A&A, 293, 363
Pogodin M. A., 1997, A&A, 317, 185
Pojmanski G., 1997, Acta Astron., 47, 467
Przygodda F., van Boekel R., Abrahám P., Melnikov S. Y., Waters L. B. F. M., Leinert C., 2003, A&A, 412, L43
Sandell G., Salyk C., van den Ancker M., de Wit W. J., Chambers E., Gusten R., Wiesemeyer H., Richter H., 2018, ApJ, 864, 104
Shappee B. J., et al., 2014, ApJ, 788, 48
Speck A. K., Barlow M. J., Hofmeister R. J., Hofmeister A. M., 2000, Astronomy and Astrophysics Supplement Series, 146, 437
Tielens A. G. G. M., 1990, in Mennessier M. O., Omont A., eds, From Miras to Planetary Nebulae: Which Path for Stellar Evolution? p. 186
Turner N. J., Carballido A., Sano T., 2010, ApJ, 708, 188
Varga J., et al., 2018, A&A, 617, A83
Vieira R. G., Carciofi A. C., Bjorkman J. E., 2015, MNRAS, 454, 2107
Wagner K., et al., 2018, ApJ, 854, 130
Waters L. B. F. M., et al., 1996, A&A, 315, L361

This paper has been typeset from a TeX/LaTeX file prepared by the author.