The Keck Aperture Masking Experiment: dust-enshrouded red giants

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ABSTRACT

While the importance of dusty asymptotic giant branch (AGB) stars to galactic chemical enrichment is widely recognized, a sophisticated understanding of the dust formation and wind-driving mechanisms has proven elusive due in part to the difficulty in spatially resolving the dust-formation regions themselves. We have observed 20 dust-enshrouded AGB stars as part of the Keck Aperture Masking Experiment, resolving all of them in multiple near-infrared bands between 1.5 and 3.1 μm. We find 45 per cent of the targets to show measurable elongations that, when correcting for the greater distances of the targets, would correspond to significantly asymmetric dust shells at par with the well-known cases of IRC + 10216 or CIT 6. Using radiative transfer models, we find the sublimation temperature of $T_{\text{sub}}$ (silicates) = $1130 \pm 90$ K and $T_{\text{sub}}$ (amorphous carbon) = $1170 \pm 60$ K, both somewhat lower than expected from laboratory measurements and vastly below temperatures inferred from the inner edge of young stellar objects discs. The fact that O-rich and C-rich dust types showed the same sublimation temperature was surprising as well. For the most optically thick shells ($r_{2.2\mu m} > 2$), the temperature profile of the inner dust shell is observed to change substantially, an effect we suggest could arise when individual dust clumps become optically thick at the highest mass-loss rates.

Key words: radiative transfer – instrumentation: interferometers – circumstellar matter.

1 INTRODUCTION

One of the most dramatic phases in the life of an intermediate mass star is the asymptotic giant branch (AGB), a relatively short period where a star loses most of its initial mass through a dusty wind. Researchers still do not understand all the ingredients necessary for producing the high mass-loss rates observed during this stage. The massive envelopes ejected during this phase are thought to be later illuminated during the planetary nebula stage, a stage where most stars show strong departure from spherical symmetry (Balick & Frank 2002).

Following the advent of infrared (IR) detectors, early workers made simple spherically symmetric models of dusty shells around large samples of AGB stars fitting only to the spectral energy distributions (e.g. Rowan-Robinson & Harris 1982, 1983a,b). M-type stars are typically surrounded by dust shells composed of amorphous silicates while C-stars have carbonaceous dust. These early workers were able to show that dust condensed around 1000 K while C-stars have carbonaceous dust. These early workers were able to show that dust condensed around 1000 K while C-stars have carbonaceous dust.

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Here we present the full data set of dust-enshrouded giants observed with the 10-yr project called the Keck Aperture Masking Experiment (Tuthill et al. 2000b). This experiment delivered well-calibrated spatial information on the scale of ~50 milliarcseconds.
(mas) in the astronomical $K$ band ($\lambda_0 = 2.2 \mu m$), which resolves all the dusty targets presented here well enough to measure their dust shell sizes and asymmetries, although the objects were not sufficiently resolved for reliable imaging. This paper includes 20 objects with observations in typically three wavelength ranges, 1.65, 2.2 and 3.1 $\mu m$. We have also extracted photometry to construct coeval near-IR spectral energy distributions – an important factor since these objects pulsate and show large variations in flux on yearly time-scales. Lastly, we used a radiative transfer code to fit each epoch of each target star using simultaneously the NRCR photometry and multi-wavelength angular size information from Keck masking.

The primary goals of these observations and modelling efforts are to measure the physical characteristics of a large sample of the most extreme dusty AGB stars, to address the question of the onset of circumstellar asymmetries, to determine any differences between silicate and carbon-rich dust shells, and to constrain the optical properties of the dust particles themselves. Lastly, this publication marks the final large data release of AGB star data from our diffraction-limited Keck masking experiment and we anticipate that this work will provide a rich data set for more detailed modelling efforts by other workers.

2 OBSERVATIONS

2.1 Overview of observations

Our observations consist of photometric and visibility data taken on 20 different stars at the W. M. Keck Observatory between 1997 December and 2002 July. The wavelengths at which these stars were observed and the properties of the corresponding filters are listed in Table 1. A listing of the observed stars, segregated into carbon-rich and oxygen-rich groups, along with their basic properties can be found in Table 2. Most stars were measured at more than one epoch during this time span allowing for robust internal data quality checks.

2.2 Photometric data

Aperture masking procedures consist of alternating target and calibrator observations that allow for basic photometry in most observing conditions. As part of the standard pipeline (Monnier 1999; Tuthill et al. 2000b), we performed aperture photometry on each object, allowing for the difference in magnitude ($\Delta$mag) between the target star and the calibrator star to be measured. The VizieR catalogue service, most often referencing the Catalogue of Infrared Observations (Gazari, Pitts & Schmitz 1993) and Two Micron All Sky Survey (2MASS) (Skrutskie et al. 2006), was used to determine magnitudes at IR wavelengths for the calibrators. Interpolation was used between wavelengths found in the catalogues and the wavelengths at which our data were measured.

Table 1. Properties of NIRC camera infrared filters. Reference: The NIRC Manual.

| Name      | Center wavelength $\lambda_0$ (\(\mu m\)) | Bandpass FWHM $\Delta \lambda$ (\(\mu m\)) | Fractional bandwidth (per cent) |
|-----------|------------------------------------------|---------------------------------------------|---------------------------------|
| FeII      | 1.6471                                   | 0.0176                                      | 1.1                             |
| H         | 1.6575                                   | 0.333                                       | 20                              |
| K         | 2.2135                                   | 0.427                                       | 19                              |
| Kcont     | 2.259 65                                 | 0.0531                                      | 2.3                             |
| CH4       | 2.269                                    | 0.155                                       | 6.8                             |
| PArCs     | 3.0825                                   | 0.1007                                      | 3.3                             |

Table 2. Basic properties of targets.

| Source names | RA (J2000) $^{(h\,m\,s)}$ | Dec. (J2000) $^{(\circ\,'\,'\,')}$ | V (mag) | J$^a$ (mag) | H$^a$ (mag) | K$^a$ (mag) | Spectral type |
|--------------|--------------------------|----------------------------------|---------|-------------|-------------|-------------|---------------|
| AFGL 230     | 01 33 51.21              | +26 26 53.5                     | 20.2(2) | 6.338       | 4.035       | 2.616       | M$^0$(1)     |
| AFGL 2019    | 17 53 18.9               | +26 56 37                      |         |             |             |             |               |
| AFGL 2199    | 18 35 46.46              | +05 35 46.5                    | 8.04    | 4.85        | 2.701       |             | M$^0$(6)     |
| AFGL 2290    | 18 58 30.2               | +06 42 57.7                    | 13.169  | 8.966       | 5.862       |             | M$^0$(6)     |
| CIT 1        | 00 06 52.94              | +03 05 00.0                    | 9.00(1) | 3.041       | 1.829       | 1.115       | M$^0$(1)     |
| CIT 3        | 01 06 25.98              | +12 35 53.0                    |         | 7.45        | 4.641       | 2.217       | M$^0$(1)     |
| v1300 Aql    | 20 10 27.87              | -06 16 13.6                    |         | 6.906       | 3.923       | 2.059       | M$^0$(1)     |
| AFGL 1922    | 17 07 58.24              | -24 44 31.1                    | 12.244  | 9.181       | 6.342       |             | C$^3$(3)     |
| AFGL 1977    | 17 31 54.98              | +17 45 19.7                    | 9.9(4)  | 10.536      | 7.994       | 5.607       | C$^1$(1)     |
| AFGL 2135    | 18 22 34.50              | +27 06 30.2                    |         | 9.043       | 6.002       | 3.643       | C$^1$(1)     |
| AFGL 2252    | 18 41 54.98              | +17 41 08.5                    | 9.7(1)  | 5.742       | 3.444       | 1.744       | C$^1$(1)     |
| AFGL 2513    | 20 09 14.22              | +31 25 44.0                    |         | 8.229       | 5.705       | 3.69        | C$^1$(1)     |
| AFGL 2666    | 20 59 08.88              | +27 26 41.7                    | 20(1)   | 9.112       | 6.268       | 4.075       | C$^1$(3)     |
| AFGL 4211    | 15 11 41.89              | -48 20 01.3                    |         | 10.711      | 7.751       | 5.154       | C$^1$(3)     |
| IRAS 15148—4940 | 15 18 22.05          | -49 51 04.6                    | 11.8(1) | 5.297       | 3.071       | 1.696       | C$^1$(1)     |
| 1Y Hya       | 10 17 00.52              | -14 39 31.4                    | 14(1)   | 5.919       | 3.666       | 1.964       | C$^5$(1)     |
| LP And       | 23 34 27.66              | +43 33 02.4                    |         | 9.623       | 6.355       | 3.859       | C$^5$(1)     |
| RV And       | 21 05 51.68              | -00 12 40.3                    | 11.5(1) | 4.046       | 2.355       | 1.239       | C$^5$(1)     |
| v1899 Cyg    | 21 04 14.8               | +53 21 03                      | 15.6(1) | 10.84       | 6.893       | 6.596       | C$^5$(1)     |
| V Cyg        | 21 41 18.2702            | +48 08 28.835                  | 7.7(1)  | 3.096       | 1.273       | 0.117       | C$^1$(1)     |

$^a$These magnitudes (from 2MASS) are merely representative since the targets are variable. See Table 3 for our new photometry.

*Note. The horizontal line separates oxygen rich (top) from carbon rich (bottom). References: (1) SIMBAD, (2) Monet (1998), (3) Buscombe (1998), (4) Egret et al. (1992), (5) Skiff (2009), (6) Olnon (1986) – see also www.iras.ucalgary.ca/~volk/getlrs_plot.html, (7) Garcia-Hernandez et al. (2007).
| Target         | Date(s) (UT)      | Filter | Aperture mask | Magnitude       | Calibrator names |
|----------------|-------------------|--------|---------------|-----------------|------------------|
| AFGL 230       | 1997 December k   | FFA    |                | 8.34 ± 0.1      | χ Cas           |
|                | 2002 July k       | FFA    |                | 8.99 ± 0.1      | HD 9878         |
| AFGL 2019      | 2000 June CH4     | annulus 36 |                | 2.48 ± 0.1      | HD 163428       |
|                | h                 | annulus 36 |                | 3.84 ± 0.1      | HD 156992       |
| AFGL 2199      | 1998 April CH4    | annulus 36 |                | 2.99 ± 0.1      | HD 170137       |
| AFGL 2290      | 1998 June CH4     | annulus 36 |                | 4.72 ± 0.1      | HD 173074       |
|                | k                 | annulus 36 |                | 2.60 ± 0.1      | HD 173074       |
|                | PAHcs             | annulus 36 |                | 5.61 ± 0.1      | HD 173833       |
|                | PAHcs             | annulus 36 |                | 6.19 ± 0.32     | HD 231437       |
|                | PAHcs             | annulus 36 |                | 3.29 ± 0.1      | HD 173833       |
| CIT 1          | 2000 June CH4     | annulus 36 |                | 2.60 ± 0.1      | λ And           |
|                | h                 | annulus 36 |                | 4.18 ± 0.25     | HD 222499       |
|                | PAHcs             | annulus 36 |                | 1.51 ± 0.1      | λ And           |
| CIT 3          | 1997 December Kcont | annulus 36 |                | 1.08 ± 0.1      | δ Psc          |
|                | PAHcs             | annulus 36 |                | −0.14 ± 0.1     | δ Psc          |
|                | 1998 September CH4 | Golay 21 |                | 2.45 ± 0.1      | δ Psc          |
|                | CH4               | annulus 36 |                | 1.04 ± 0.1      | δ Psc          |
| v1300 Aql      | 1998 June CH4     | annulus 36 |                | 1.39 ± 0.1      | HD 189114       |
|                | h                 | annulus 36 |                | 3.29 ± 0.25     | HD 192464       |
|                | PAHcs             | annulus 36 |                | 0.60 ± 0.1      | HD 189114       |
|                | k                 | annulus 36 |                | 2.02 ± 0.1      | SAO 14382       |
|                | PAHcs             | annulus 36 |                | 0.86 ± 0.1      | SAO 14382       |
| AFGL 1922      | 2000 June k       | annulus 36 |                | 6.34 ± 0.25     | HD 156992       |
|                | PAHcs             | annulus 36 |                | 3.62 ± 0.25     | HD 158774       |
| AFGL 1977      | 1998 June CH4     | annulus 36 |                | 4.19 ± 0.1      | HD 158227       |
|                | h                 | annulus 36 |                | 7.05 ± 0.1      | HD 158227       |
|                | PAHcs             | annulus 36 |                | 1.84 ± 0.1      | HD 157049       |
| AFGL 2135      | 2001 June k       | annulus 36 |                | 3.29 ± 0.1      | HD 168366, HD 181700 |
| AFGL 2232      | 1998 June CH4     | annulus 36 |                | 2.04 ± 0.1      | HD 158227       |
|                | h                 | annulus 36 |                | 4.12 ± 0.1      | HD 158227       |
|                | PAHcs             | annulus 36 |                | 0.68 ± 0.1      | HD 157049       |
| AFGL 2513      | 1998 September h  | annulus 36 |                | 6.58 ± 0.1      | HD 196241       |
| AFGL 2686      | 1998 September h  | annulus 36 |                | 4.03 ± 0.1      | HD 200451       |
| AFGL 2290      | 1999 April CH4    | annulus 36 |                | 1.06 ± 0.1      | HD 173833       |
|                | h                 | annulus 36 |                | −0.38 ± 0.1     | HD 173833       |
| AFGL 4211      | 2000 June CH4     | annulus 36 |                | 3.62 ± 0.3      | HD 137709       |
|                | h                 | annulus 36 |                | 8.48 ± 0.3      | HD 137709       |
| AFGL 4211      | 2001 June k       | annulus 36 |                | 4.70 ± 0.1      | HD 137709       |
| IRAS 15148−4940| 2001 June CH4     | annulus 36 |                | 1.25 ± 0.3      | HD 137709       |
|                | k                 | annulus 36 |                | 1.30 ± 0.3      | HD 137709       |
|                | PAHcs             | annulus 36 |                | 1.71 ± 0.1      | HD 136422       |
Table 3 – continued

| Target     | Date(s) (UT) | Filter | Aperture mask | Magnitude | Calibrator names |
|------------|--------------|--------|---------------|-----------|------------------|
| IY Hya     | 1999 April   | CH4    | annulus 36    | 2.08 ± 0.1| HD 87262         |
|            |              | PAHcs  | annulus 36    | 1.37 ± 0.1| μ Hya            |
| LP And     | 1998 September| CH4    | annulus 36    | 3.89 ± 0.1| HD 222499, λ And |
|            |              | h      | annulus 36    | 7.05 ± 0.25| HD 222499        |
|            |              | PAHcs  | annulus 36    | 1.72 ± 0.1| λ And           |
|            | 1999 July    | CH4    | Golay 21      | 4.01 ± 0.1| α Cas           |
|            |              | PAHcs  | Golay 21      | 1.80 ± 0.1| α Cas           |
|            | 1999 January | CH4    | Golay 21      | 3.26 ± 0.1| α Cas           |
|            |              | PAHcs  | Golay 21      | 1.18 ± 0.1| α Cas           |
| RV Aqr     | 1999 July    | CH4    | Golay 21      | 1.23 ± 0.25| SAO 143482, 3 Aqr|
|            |              | PAHcs  | Golay 21      | 0.56 ± 0.25| SAO 143482, 3 Aqr|
|            | 1998 June    | CH4    | Golay 21      | 1.52 ± 0.1| HD 196321       |
|            |              | PAHcs  | Golay 21      | 1.15 ± 0.1| HD 196321       |
| v1899 Cyg  | 1998 June    | CH4    | annulus 36    | 5.53 ± 0.1| HD 202897       |
|            |              | h      | annulus 36    | 7.87 ± 0.3| HD 200817       |
|            |              | PAHcs  | annulus 36    | 3.71 ± 0.1| HD 202897       |
|            | 1999 July    | k      | annulus 36    | 6.40 ± 0.1| HD 198661       |
|            |              | PAHcs  | KL relation*  | 4.72 ± 0.2|                 |
| V Cyg      | 1998 June    | feii   | annulus 36    | 2.59 ± 0.1| HD 192909       |
|            |              | kcont  | annulus 36    | 0.53 ± 0.1| HD 192909       |
|            |              | CH4    | Golay 21      | 0.50 ± 0.1| HD 192909       |
|            |              | PAHcs  | annulus 36    | 0.26 ± 0.1| HD 192909       |
|            | 1999 April   | CH4    | Golay 21      | 0.19 ± 0.1| HD 192909       |
|            |              | PAHcs  | Golay 21      | −0.25 ± 0.1| π Cyg          |
|            | 2001 June    | CH4    | annulus 36    | −0.27 ± 0.1| π Cyg          |
|            |              | PAHcs  | annulus 36    | −0.69 ± 0.1| π Cyg          |

*This point was extrapolated from another epoch for the same star and assigned an error of 0.2 mag.

Note: The horizontal line separates oxygen rich (top) from carbon rich (bottom).

taken. Occasionally no near-IR measurements were available for some calibrators and we used the calibrator spectral type and the $K$-band flux to estimate the flux density at these longer wavelengths.

As a data quality check, we compared our photometry with 2MASS and found good general agreement, although strict agreement was not expected since our targets are highly variable and there is some difference in beam sizes. We estimated the error on the photometry points at 10 per cent based on night-to-night variations. However, there were instances when we assigned larger errors (between 10 and 32 per cent) due to saturation of the 2MASS photometry used for the calibrator, intrinsic variability of the calibrator or effects of cirrus clouds in some of the original data. Indeed, there were some nights too contaminated by variable clouds to allow photometry to be extracted at all.

Table 3 is a journal of observations, including the observing date(s), the filter(s) used, the aperture mask(s) used and the calibrator star name. We have compiled the adopted calibrator properties in Table 4.

2.3 Visibility data

2.3.1 Methodology

Our group carried out aperture masking interferometry at the Keck-1 telescope from 1996 to 2005. We have published images and size measurements with (at the time) unprecedented angular resolution on topics ranging from young stellar objects, carbon stars, red supergiants and photospheric diameters of Mira variables (e.g. Monnier et al. 1999; Tuthill et al. 2000a,b; Danchi, Tuthill & Monnier 2001).

The Near Infrared Camera (NIRC) camera with the image magnifier (Matthews et al. 1996) was used in conjunction with the aperture masking hardware to create fringes at the image plane. The data frames were taken in speckle mode ($T_{\text{int}} = 0.14\ \text{s}$) to freeze the atmosphere. In the work presented here, multiple aperture masks and bandpass filters were employed. After flat-fielding, bad pixel correction and sky-subtraction, Fourier methods were used to extract fringe visibilities and closure phases from each frame and averaged in groups of 100 frames. Absolute calibration to account for the optical transfer function and decoherence from atmospheric seeing was performed by interleaving science observations with measurements of unresolved calibrator stars. At the end of the pipeline, the data products are purely interferometric as if obtained with a long-baseline interferometer. A full description of this experiment can be found in Tuthill et al. (2000b) and Monnier (1999), with further discussion of systematic errors in Monnier et al. (2004, 2007). All $V^2$ and closure phase data are available from the authors; all data products are stored in the Flexible Image Transport System (FITS)-based, optical interferometry data exchange format (OI-FITS), as described in Pauls et al. (2005).

2.3.2 Basic results

Before undertaking radiative transfer modelling, we provide the results of basic geometrical analysis of the visibility data.
Table 4. Basic properties of calibrators.

| Calibrator | J (mag) | H (mag) | K (mag) | PAHs (mag) | Reference |
|------------|--------|--------|--------|-----------|-----------|
| HD 168720  | 1.79   | 0.875  | 0.870  | 0.794     | McWilliam & Lambert (1984), Skrutskie (2006), Neugebauer & Leighton (1969) |
| HD 170137  | 3.476  | 2.737  | 2.230  | 2.16      | Skrutskie (2006), Neugebauer & Leighton (1969) |
| ε Cyg     | 0.641  | 0.2    | 0.1    | 0.011     | Neugebauer & Leighton (1969), Ghosh et al. (1984), Price & Murdock (1983) |
| HD 200451  | 4.101  | 3.231  | 2.840  | –         | Skrutskie (2006), Neugebauer & Leighton (1969) |
| HD 231437  | 5.027  | 3.958  | 3.693  | –         | Skrutskie (2006) |
| HD 173833  | 3.488  | 2.647  | 2.1    | 2.02      | Skrutskie (2006), Neugebauer & Leighton (1969) |
| HD 158227  | 5.626  | 4.984  | 4.812  | –         | Skrutskie (2006), Neugebauer & Leighton (1969) |
| HD 157049  | 1.975  | 1.149  | 0.830  | 0.684     | Skrutskie (2006), Neugebauer & Leighton (1969), Price & Murdock (1983) |
| HD 168366  | 5.049  | 4.535  | 4.255  | –         | Skrutskie (2006) |
| HD 181700  | 3.938  | 2.993  | 2.735  | –         | Skrutskie (2006) |
| SAO 143482 | 1.665  | 0.790  | 0.573  | 0.436     | Skrutskie (2006), Gullixson et al. (1983) |
| HD 189114  | 3.212  | 2.030  | 1.953  | 1.908     | Skrutskie (2006), Gosnell, Hudson & Peutter (1979) |
| HD 137709  | 2.232  | 1.532  | 1.331  | 1.257     | Skrutskie (2006), extrapolation |
| HD 222499  | 4.641  | 3.804  | 3.627  | –         | Skrutskie (2006) |
| λ And     | 1.970  | 1.4    | 1.287  | 1.245     | Johnson et al. (1966), Price & Murdock (1983), Selby et al. (1988) |
| HD 9878   | 6.631  | 6.730  | 6.698  | –         | Skrutskie (2006) |
| HD 9329   | 4.961  | 4.381  | 4.341  | 4.29      | Skrutskie (2006), extrapolation |
| HD 156992  | 3.901  | 3.123  | 2.926  | –         | Skrutskie (2006) |
| HD 158774  | 4.403  | 3.451  | 3.138  | –         | Skrutskie (2006), Kawara et al. (1983) |
| HD 198611  | 3.755  | 2.862  | 2.470  | –         | Skrutskie (2006), Neugebauer & Leighton (1969) |
| HD 202987  | 3.859  | 3.067  | 2.82   | 2.75      | Skrutskie (2006), Neugebauer & Leighton (1969) |
| 3 Aqr     | 0.934  | –0.020 | –0.220 | –0.338    | Carter (1990) |
| HD 192999  | 1.190  | –0.180 | 0.101  | –         | Johnson et al. (1966), Neugebauer & Leighton (1969), Price & Murdock (1983) |
| ε Cyg     | 0.995  | 0.130  | –0.070 | –0.150    | Johnson et al. (1966), Noguchi et al. (1981) |
| HD 200817  | 4.174  | 3.721  | 3.708  | –         | Skrutskie (2006) |
| HD 192464  | 5.180  | 4.176  | 3.879  | –         | Skrutskie (2006) |
| α Cas     | 0.371  | –0.191 | –0.270 | –0.399    | Voelecker (1975), Alonso, Arribas & Martinez-Roger (1994) |
| μ Hya     | 1.216  | 0.506  | 0.37   | 0.28      | Skrutskie (2006), Price & Murdock (1983), Johnson et al. (1966) |
| HD 87262  | 2.974  | 2.052  | 1.880  | –         | Skrutskie (2006), Price & Murdock (1983), Neugebauer & Leighton (1969) |
| HD 196321  | 2.128  | 1.361  | 1.21   | 0.98496   | Skrutskie (2006), Price & Murdock (1983), Neugebauer & Leighton (1969) |
| HD 136422  | –     | –      | 0.8    | 0.535     | Price (1968), Price & Murdock (1983), Eggen (1969) |
| δ Psc     | 2.031  | 1.198  | 0.890  | 0.739     | Skrutskie (2006), Gosnell et al. (1979) |
| HD 198330  | 4.988  | 4.159  | 3.816  | –         | Skrutskie (2006) |
| HD 188947  | 1.934  | 1.438  | 1.621  | 1.561     | Noguchi et al. (1981), Elias et al. (1982), Glass (1975) |
| χ Cas     | 3.019  | 2.481  | 2.311  | –         | Skrutskie (2006), Neugebauer & Leighton (1969) |
| HD 163428  | –     | 1.6    | 1.464  | –         | White & Wing (1978), Humphreys & Ney (1974) |
| HD 196241  | 4.19   | 3.620  | 3.090  | –         | Morel & Magnenat (1978), Skrutskie (2006) |

The simplest representation of the data is generally a circularly symmetric Gaussian envelope, a useful model to give a characteristic size to the emission. Table 5 provides the visibility intercept, \( V_0 \) (the visibility at zero baseline), and the full width at half-maximum (FWHM) for the best fit for all data sets, including the reduced \( \chi^2 \). Errors are generally dominated by systematics related to the calibration procedure (i.e. seeing variation between source and calibrator visits) and we have used the relations established in Monnier et al. (2007) to quantify our errors. In some cases, there was evidence of two components to the visibility curve and we have also fitted a slightly more complex model of a point source plus a Gaussian envelope to all epochs. Table 6 contains the best-fitting parameters of the two-component model, including the estimated fraction of light in the point source \( f_{\text{point}} \) and the fraction of light in the Gaussian envelope \( f_{\text{Gauss}} \).

In addition, we fitted each object with a two-dimensional Gaussian function in order to search for signs of asymmetry. Objects with observed asymmetry are marked with an asterisk in Table 5. Table 7 lists all the objects with confirmed asymmetries and we include the amount of elongation \( \frac{\text{FWHM}_{\text{major}}}{\text{FWHM}_{\text{minor}}} \) and the position angle (PA; degrees east of north) of the major axis. Here we have used the spread of measured position angles between wavelength channels and epochs to estimate the PA error. We will discuss further these findings in Section 4.

3 DUST SHELL MODELLING

3.1 Introduction

The objects in our study all have spectral energy distributions that peak in the IR. Indeed, these stars are surrounded by dust shells that absorb the stellar light and then re-emit the energy in the IR. In order to extract physical characteristics of these dust shells (i.e. optical depths, temperatures, etc.), we must be able to compute how the dust will absorb, scatter and re-emit the energy from the star. We accomplish this with the radiative-transfer model \textsc{dusty} (Ivezić, Nenkova & Elitzur 1999). While \textsc{dusty} is limited to calculations in spherical symmetry, we established in the previous section that most of our objects show only mild signs of global asymmetries; however, we caution that our results will be suspect for the most asymmetric of the targets listed in Table 7. Given a small number of input parameters, \textsc{dusty} can quickly compute synthetic photometry...
Table 5. Results from circularly symmetric Gaussian models.

| Target | Date(s)       | Filter | Aperture | $V_0$ (±0.05) | FWHM (mas) | $\chi^2$/DOF |
|--------|---------------|--------|----------|---------------|------------|--------------|
| AFGL 230 | 1997 December | k      | FFA      | 0.71          | 32 ± 3     | 0.23         |
|         | 2002 July     | k      | PAHcs    | 0.74          | 33 ± 2     | 0.05         |
|         |               |        | FFA      | 0.74          | 33 ± 2     | 0.05         |
| AFGL 2019 | 2000 June    | CH4    | annulus 36 | 0.96          | 10$^{+6}_{-10}$ | 0.31       |
|         |               | h      | annulus 36 | 0.90          | 9 ± 4     | 0.65         |
|         |               |        | PAHcs    | 0.95          | 21 ± 3     | 0.27         |
| AFGL 2199 | 1998 April   | CH4    | annulus 36 | 0.92          | 14 ± 6     | 0.23         |
|         |               |        | PAHcs    | 1.00          | 22 ± 3     | 0.45         |
| AFGL 2290* | 1998 June    | CH4    | annulus 36 | 0.76          | 22 ± 4     | 0.33         |
|         |               |        | PAHcs    | 0.84          | 27 ± 3     | 0.69         |
|         | 1999 April    | CH4    | annulus 36 | 0.72          | 34 ± 3     | 0.39         |
|         |               |        | PAHcs    | 0.75          | 32 ± 3     | 0.51         |
| Cit 1*  | 2000 June     | CH4    | annulus 36 | 0.92          | 15 ± 5     | 0.35         |
|         |               | h      | annulus 36 | 0.93          | 14 ± 3     | 0.37         |
|         |               |        | PAHcs    | 0.94          | 20 ± 4     | 0.46         |
| Cit 3*  | 1997 December | k      | annulus 36 | 0.89          | 20 ± 5     | 0.44         |
|         |               |        | PAHcs    | 0.89          | 37 ± 2     | 0.21         |
|         | 1998 September| CH4    | Golay 21  | 0.89          | 21 ± 4     | 0.35         |
|         |               |        | PAHcs    | 0.90          | 29 ± 2     | 0.25         |
| v1300 Aql* | 1998 June    | CH4    | annulus 36 | 0.83          | 14 ± 6     | 0.43         |
|         |               | h      | annulus 36 | 0.81          | 14 ± 3     | 0.41         |
|         |               |        | PAHcs    | 0.84          | 23 ± 3     | 0.50         |
|         | 1999 July     | k      | annulus 36 | 0.87          | 18 ± 5     | 0.39         |
|         |               |        | PAHcs    | 0.90          | 21 ± 3     | 0.52         |
| AFGL 1922 | 2000 June    | k      | annulus 36 | 0.76          | 24 ± 4     | 0.88         |
|         | 2001 June     | k      | annulus 36 | 0.83          | 29 ± 4     | 0.76         |
|         |               |        | PAHcs    | 0.95          | 58 ± 2     | 0.43         |
| AFGL 1977* | 1998 June    | CH4    | annulus 36 | 0.78          | 24 ± 4     | 0.26         |
|         |               | h      | annulus 36 | 0.76          | 17 ± 3     | 0.68         |
|         |               |        | PAHcs    | 0.94          | 34 ± 2     | 0.41         |
|         | 1999 April    | CH4    | annulus 36 | 0.96          | 29 ± 4     | 0.25         |
|         |               |        | PAHcs    | 0.89          | 52 ± 2     | 0.26         |
| AFGL 2135 | 2001 June     | k      | annulus 36 | 0.66          | 17 ± 5     | 0.49         |
|         | 2001 June     |      | PAHcs    | 0.50          | 34 ± 2     | 0.13         |
| AFGL 2232* | 1998 June    | CH4    | annulus 36 | 0.83          | 18 ± 5     | 1.32         |
|         |               | h      | annulus 36 | 0.81          | 14 ± 3     | 0.50         |
|         |               |        | PAHcs    | 0.90          | 33 ± 2     | 0.56         |
|         | 1999 April    | CH4    | Golay 21  | 0.91          | 20 ± 5     | 0.17         |
|         |               |        | PAHcs    | 0.90          | 34 ± 2     | 0.14         |
|         |               |        | PAHcs    | 0.69          | 44 ± 3     | 0.19         |
| AFGL 2513* | 1998 September| h    | annulus 36 | 1.00          | 1$^{+5}_{-1}$ | 1.15       |
|         |               |        | CH4      | 0.94          | 10$^{+10}_{-11}$ | 0.18       |
|         |               |        | PAHcs    | 1.00          | 16 ± 4     | 0.70         |
|         | 1999 July     | CH4    | annulus 36 | 1.00          | 11$^{+6}_{-10}$ | 0.32       |
|         |               |        | PAHcs    | 0.96          | 24 ± 3     | 0.36         |
| AFGL 2686 | 1998 September| CH4    | annulus 36 | 0.89          | 29 ± 4     | 0.44         |
|         |               | h      | annulus 36 | 0.89          | 26 ± 2     | 0.47         |
|         |               |        | PAHcs    | 0.89          | 35 ± 2     | 0.36         |
|         | 1999 July     | CH4    | annulus 36 | 0.92          | 26 ± 4     | 0.68         |
|         |               |        | PAHcs    | 0.91          | 33 ± 2     | 0.44         |
|         |               | h      | annulus 36 | 0.77          | 28 ± 2     | 0.87         |
| AFGL 4211 | 2000 June     | CH4    | annulus 36 | 0.78          | 31 ± 3     | 0.48         |
|         | 2001 June     | k      | annulus 36 | 0.82          | 70 ± 3     | 0.10         |
| IRAS 15148—4940 | 2001 June | CH4    | annulus 36 | 0.77          | 13 ± 7     | 0.41         |
|         |               | k      | annulus 36 | 0.82          | 13 ± 7     | 0.59         |
|         |               |        | PAHcs    | 0.86          | 25 ± 3     | 0.39         |
| IY Hya  | 1999 April    | CH4    | annulus 36 | 0.88          | 14 ± 6     | 0.32         |
|         |               |        | PAHcs    | 0.94          | 33 ± 2     | 0.28         |
Table 5 – continued

| Target       | Date(s)      | Filter | Aperture | \( V_0 \) (±0.05) | FWHM (mas) | \( \chi^2/DOF \) |
|--------------|--------------|--------|----------|-------------------|------------|------------------|
| LP And*      | 1998 September | CH4    | annulus 36 | 0.83             | 25 ± 4     | 0.52             |
|              |              | h      | annulus 36 | 0.68             | 20 ± 3     | 0.56             |
|              |              | PAHcs  | annulus 36 | 0.86             | 47 ± 2     | 0.49             |
|              | 1999 July    | CH4    | Golay 21  | 0.89             | 24 ± 4     | 0.99             |
|              |              | PAHcs  | Golay 21  | 0.79             | 48 ± 2     | 0.50             |
|              | 1999 January | CH4    | Golay 21  | 0.70             | 25 ± 4     | 2.41             |
|              |              | PAHcs  | Golay 21  | 0.66             | 35 ± 2     | 0.45             |
| RV Aqr*      | 1999 July    | CH4    | Golay 21  | 1.00             | 8 ± 8      | 0.16             |
|              |              | PAHcs  | Golay 21  | 0.96             | 26 ± 3     | 0.21             |
|              | 1998 June    | CH4    | Golay 21  | 0.98             | 12 ± 8     | 0.13             |
|              |              | PAHcs  | Golay 21  | 1.00             | 27 ± 3     | 0.36             |
| v1899 Cyg    | 1998 June    | CH4    | annulus 36 | 0.88             | 18 ± 5     | 0.35             |
|              |              | h      | annulus 36 | 0.86             | 16 ± 3     | 0.39             |
|              |              | PAHcs  | annulus 36 | 0.92             | 22 ± 3     | 0.32             |
|              | 1999 July    | k      | annulus 36 | 0.93             | 15 ± 5     | 0.62             |
| V Cyg        | 1998 June    | feii   | annulus 36 | 0.87             | 14 ± 3     | 0.92             |
|              |              | kcont  | annulus 36 | 0.96             | 16 ± 5     | 1.15             |
|              |              | PAHcs  | annulus 36 | 0.90             | 34 ± 2     | 0.51             |
|              | 1999 April   | CH4    | Golay 21  | 1.00             | 18 ± 5     | 0.35             |
|              |              | PAHcs  | Golay 21  | 0.92             | 38 ± 2     | 0.10             |
|              | 2001 June    | CH4    | annulus 36 | 0.82             | 19 ± 5     | 0.26             |
|              |              | PAHcs  | annulus 36 | 0.83             | 42 ± 2     | 0.15             |

*Target is asymmetric; see Table 7 for further details.

Note. The horizontal line separates oxygen rich (top) from carbon rich (bottom).

Table 6. Results from central point plus circularly symmetric Gaussian models.

| Target     | Date(s)  | Filter | Aperture | \( f_{\text{Point}} \) (±0.05) | \( f_{\text{Gauss}} \) (±0.05) | FWHM (mas) | \( \chi^2/DOF \) |
|------------|----------|--------|----------|-------------------|-------------------|------------|------------------|
| AFGL 230   | 1997 December | k      | FFA      | 0.24              | 0.52              | 47 ± 7     | 0.21             |
|            | 2002 July | k      | FFA      | 0.30              | 0.42              | 98 ± 7     | 0.15             |
|            |          | PAHcs  | FFA      | 0.50              | 0.32              | 86 ± 8     | 0.42             |
| AFGL 2019  | 2000 June | CH4    | annulus 36 | 0.86             | 0.14             | 51 ± 30    | 0.28             |
|            |          | h      | annulus 36 | 0.00             | 0.83             | 1.9 ± 0.45 | 0.83             |
|            |          | PAHcs  | annulus 36 | 0.45             | 0.51             | 31 ± 5     | 0.27             |
| AFGL 2199  | 1998 April | CH4    | annulus 36 | 0.38             | 0.54             | 19 ± 9     | 0.22             |
|            |          | PAHcs  | annulus 36 | 0.36             | 0.68             | 30 ± 4     | 0.43             |
| AFGL 2290* | 1998 June | CH4    | annulus 36 | 0.44             | 0.38             | 46 ± 12    | 0.26             |
|            |          | PAHcs  | annulus 36 | 0.55             | 0.38             | 68 ± 7     | 0.61             |
|            | 1999 April | CH4    | annulus 36 | 0.31             | 0.51             | 66 ± 9     | 0.21             |
|            |          | k      | annulus 36 | 0.34             | 0.56             | 66 ± 9     | 0.31             |
|            |          | PAHcs  | annulus 36 | 0.25             | 0.60             | 49 ± 3     | 0.35             |
| CIT 1*     | 2000 June | CH4    | annulus 36 | 0.00             | 0.92             | 14 ± 6     | 0.35             |
|            |          | h      | annulus 36 | 0.47             | 0.49             | 23 ± 6     | 0.36             |
|            |          | PAHcs  | annulus 36 | 0.00             | 0.94             | 20 ± 4     | 0.46             |
| CIT 3*     | 1997 December | kcont | annulus 36 | 0.58             | 0.50             | 53 ± 13    | 0.23             |
|            | 1998 September | CH4    | Golay 21  | 0.50             | 0.44             | 40 ± 10    | 0.03             |
|            |          | PAHcs  | Golay 21  | 0.46             | 0.47             | 50 ± 5     | 0.20             |
| v1300 Aql* | 1998 June | CH4    | annulus 36 | 0.64             | 0.23             | 43 ± 20    | 0.40             |
|            |          | h      | annulus 36 | 0.45             | 0.38             | 25 ± 7     | 0.39             |
|            |          | PAHcs  | annulus 36 | 0.64             | 0.34             | 80 ± 10    | 0.30             |
|            | 1999 July | kcont  | annulus 36 | 0.00             | 0.87             | 18 ± 5     | 0.39             |
|            |          | PAHcs  | annulus 36 | 0.17             | 0.73             | 24 ± 4     | 0.52             |
| AFGL 1922  | 2000 June | k      | annulus 36 | 0.42             | 0.39             | 47 ± 11    | 0.83             |
|            |          | PAHcs  | annulus 36 | 0.51             | 0.47             | 105 ± 6    | 0.41             |
Table 6 – continued

| Target         | Date(s)       | Filter | Aperture | $f_{\text{Point}}$ (±0.05) | $f_{\text{Gauss}}$ (±0.05) | FWHM (mas) | $\chi^2$/DOF |
|----------------|---------------|--------|----------|-----------------------------|-----------------------------|------------|--------------|
| AFGL 1977*     | 1998 June     | CH4    | annulus 36 | 0.36                         | 0.45                        | 41 ± 9     | 0.22         |
|                | 1999 April    | CH4    | annulus 36 | 0.34                         | 0.69                        | 43 ± 7     | 0.17         |
|                | 2001 June     | PAHcs  | annulus 36 | 0.28                         | 0.27                        | 78 ± 6     | 0.10         |
|                | 1999 April    | CH4    | annulus 36 | 0.56                         | 0.33                        | 44 ± 14    | 0.47         |
| AFGL 2135      | 2001 June     | k      | annulus 36 | 0.00                         | 0.66                        | 17 ± 5     | 0.49         |
| AFGL 2232*     | 1998 June     | CH4    | annulus 36 | 0.30                         | 0.50                        | 42 ± 13    | 0.59         |
|                | 1999 April    | CH4    | Golay 21  | 0.52                         | 0.45                        | 39 ± 10    | 0.10         |
|                | 1999 April    | PAHcs  | Golay 21  | 0.35                         | 0.60                        | 51 ± 4     | 0.09         |
| AFGL 2513*     | 1998 September| h      | annulus 36 | 0.03                         | 1.00                        | $1^{+9}_{-1}$ | 1.09         |
|                | 1999 July     | CH4    | annulus 36 | 0.81                         | 0.14                        | 39 ± 39    | 0.17         |
|                | 2001 June     | k      | annulus 36 | 0.67                         | 0.37                        | 65 ± 9     | 0.24         |
| AFGL 2686      | 1998 September| CH4    | annulus 36 | 0.30                         | 0.63                        | 42 ± 7     | 0.39         |
|                | 1999 July     | CH4    | annulus 36 | 0.21                         | 0.73                        | 32 ± 5     | 0.67         |
|                | 2001 June     | k      | annulus 36 | 0.16                         | 0.70                        | 89 ± 4     | 0.06         |
| AFGL 4211      | 2000 June     | CH4    | annulus 36 | 0.36                         | 0.54                        | 59 ± 10    | 0.27         |
|                | 2001 June     | k      | annulus 36 | 0.47                         | 0.28                        | 86 $^{+10}_{-10}$ | 0.45         |
| IRAS 15148—4940| 2001 June     | CH4    | annulus 36 | 0.32                         | 0.88                        | 44 ± 23    | 0.39         |
|                | 1999 April    | CH4    | annulus 36 | 0.39                         | 0.56                        | 58 ± 4     | 0.29         |
|                | 2001 June     | h      | annulus 36 | 0.24                         | 0.69                        | 35 ± 4     | 0.43         |
|                | 1999 July     | CH4    | annulus 36 | 0.21                         | 0.73                        | 32 ± 5     | 0.67         |
|                | 2001 June     | PAHcs  | annulus 36 | 0.29                         | 0.64                        | 45 ± 3     | 0.42         |
|                | 1999 July     | h      | annulus 36 | 0.30                         | 0.50                        | 138 $^{+15}_{-9}$ | 0.77         |
| AFGL 4211      | 2000 June     | CH4    | annulus 36 | 0.36                         | 0.54                        | 59 ± 10    | 0.27         |
|                | 2001 June     | k      | annulus 36 | 0.32                         | 0.65                        | 74 ± 4     | 0.35         |
| IY Hya         | 1999 April    | CH4    | annulus 36 | 0.00                         | 0.88                        | 14 ± 6     | 0.32         |
|                | 2001 June     | h      | annulus 36 | 0.30                         | 0.65                        | 74 ± 4     | 0.35         |
| LP And*        | 1998 September| CH4    | annulus 36 | 0.42                         | 0.49                        | 49 ± 10    | 0.41         |
|                | 1999 July     | CH4    | Golay 21  | 0.47                         | 0.49                        | 47 ± 11    | 0.91         |
|                | 1999 January  | CH4    | Golay 21  | 0.35                         | 0.51                        | 85 ± 5     | 0.42         |
| RV Aqr*        | 1999 July     | CH4    | Golay 21  | 0.35                         | 0.51                        | 85 ± 5     | 0.42         |
|                | 1999 July     | CH4    | Golay 21  | 0.33                         | 0.64                        | 34 ± 4     | 0.21         |
| v1899 Cyg      | 1998 June     | CH4    | annulus 36 | 0.32                         | 0.57                        | 24 ± 7     | 0.35         |
|                | 1999 July     | k      | annulus 36 | 0.65                         | 0.23                        | 57 ± 13    | 0.31         |
| V Cyg          | 1998 June     | feii   | annulus 36 | 0.31                         | 0.56                        | 18 ± 5     | 0.91         |
|                | 1999 April    | CH4    | Golay 21  | 0.58                         | 0.47                        | 35 ± 10    | 0.30         |
|                | 2001 June     | PAHcs  | Golay 21  | 0.31                         | 0.60                        | 57 ± 4     | 0.07         |

*Target is asymmetric; see Table 7 for further details.

Note. The horizontal line separates oxygen rich (top) from carbon rich (bottom).

$f_{\text{Point}}$ is the amount of light coming from a point source and $f_{\text{Gauss}}$ is the fraction of light coming from a Gaussian envelope.
realize that a blackbody spectrum is a rather poor approximation for used a featureless Planck blackbody spectrum; however, we came to a grid of the key dust shell parameters.

We applied a uniform procedure for fitting all of our objects. Here we discuss which properties were held fixed and how we explored for every pair of \((T_{\text{dust}}, R_{\text{star}})\) we determined each star to have either carbon-rich dust or silicate-rich dust. Based on this assignment, we chose amorphous carbon (Hanner 1988) or warm amorphous silicates (Ossenkopf, Henning & Mathis 1992) in the DUSTY model setup. Speck, Whittington & Tartar (2008) discussed how silicates close to AB stars could quickly anneal to crystalline grains but a full exploration of optical constants for different grain types was beyond the scope of this work. For the grain size distribution, we adopted the standard MRN power-law grain size distribution between 0.005 and 0.25 \(\mu\)m (Mathis, Rumpl & Nordsieck 1977); a later exploration of larger grain sizes did not systematically improve fits (also see the discussion by Speck et al. 2009). Another property of the dust shell we fixed is that the dust density follows an exponential law, corresponding to constant mass-loss rate.

Lastly, we come to the parameters of the model that are not fixed: the temperature of the dust shell at the inner boundary, \(T_{\text{dust}}\)-band optical depth, \(\tau_{\text{dust}}\) and the spectral energy distribution (SED) \[\text{[and the presence of a silicate feature in IRAST-LRS (low resolution spectra)]\}, we determined each star to have either carbon-rich dust or silicate-rich dust. Based on this assignment, we chose amorphous carbon (Hanner 1988) or warm amorphous silicates (Ossenkopf, Henning & Mathis 1992) in the DUSTY model setup. Speck, Whittington & Tartar (2008) discussed how silicates close to AB stars could quickly anneal to crystalline grains but a full exploration of optical constants for different grain types was beyond the scope of this work. For the grain size distribution, we adopted the standard MRN power-law grain size distribution between 0.005 and 0.25 \(\mu\)m (Mathis, Rumpl & Nordsieck 1977); a later exploration of larger grain sizes did not systematically improve fits (also see the discussion by Speck et al. 2009). Another property of the dust shell we fixed is that the dust density follows an \(r^{-2}\) power law, corresponding to constant mass-loss rate.

Lastly, we come to the parameters of the model that are not fixed: the temperature of the dust shell at the inner boundary, \(T_{\text{dust}}\)-band optical depth, \(\tau_{\text{dust}}\) and the \(K\)-band optical depth \(\tau_{\text{dust}}\) of the dust shell (as integrated along the line of sight from the observer to the star). In the following section, we explain our fitting procedure.

### 3.3 Fitting methodology

We explored inner dust temperatures \(T_{\text{dust}}\) between 400 and 1500 K. This range explored both the high temperatures thought to be prohibitive of dust creation and low temperatures too cool for steady-state dust production. Note that when setting up a model in DUSTY, one does not specify the inner radius of the dust shell: this quantity is calculated based on the luminosity of the star and the specific inner shell dust temperature \(T_{\text{dust}}\). In terms of optical depth, we explored \(\tau_{\text{dust}}\) between 0 and 9. This range provided a full fitting region for our objects and values of \(\tau_{\text{dust}}\) much above 9 were too computationally expensive. Finally, \(R_{\text{star}}\) was recognized to simply be a scaling factor for the model outputs and could easily be optimized for every pair of \((T_{\text{dust}}, \tau_{\text{dust}})\).

For each location in the grid, we calculated the model SED as well as the radial intensity profiles. We calculated a \(\chi^2\) based on both our coeval near-IR photometry and Keck masking visibility curves. For
Table 8. Results from the DUSTY radiative transfer model.

| Target  | Date(s)      | $T_{\text{dust}}$ (K) | $\tau_{2.2\,\mu m}$ | $R_\ast$ (mas) | $L_{\text{bol}}^\ast (10^3 L_\odot)$ | $\chi^2$/DOF |
|---------|--------------|------------------------|----------------------|----------------|--------------------------------------|--------------|
| AFGL 230 | 1997 December | 800±60 / 540±400 / 110 | 4.9±0.9 / 7.4±1.6 / 1.2 | 1.5±0.5 / 4.1±4.5 / 2.1 | 4.5±3.1 / 31±108 / 31±24 | 0.26 |
| AFGL 2019 | 2000 June | 1190±310 / 250 | 0.9±0.23 / 3.5±0.7 | 24±10 / 5.4 | |
| AFGL 2199 | 1998 April | 1130±370 / 310 | 1.6±1.2 / 3.3±2.0 | 21±32 / 7 | |
| AFGL 2290 | 1998 June | 850±140 / 80 | 3.5±0.5 / 3.7±0.8 | 26±9 / 0.33 | |
| AFGL 2290 | 1999 April | 800±140 / 140 | 4.6±0.5 / 3.9±0.8 | 29±11 / 2.63 | |
| CIT 1 | 2000 June | 1190±310 / 220 | 1.2±0.5 / 3.5±0.8 | 24±12 / 0.60 | |
| CIT 3 | 1997 December | 1110±270 / 270 | 1.4±0.7 / 7.8±1.5 | 116±29 / 0.34 | |
| AFGL 1922 | 2000 June | 850±200 / 60 | 5.3±0.7 / 4.5±1.1 | 37±21 / 1.44 | |
| AFGL 1922 | 2001 June | 850±170 / 60 | 3.9±0.5 / 5.2±1.2 | 51±27 / 0.39 | |
| AFGL 1977 | 1998 June | 910±80 / 90 | 2.8±0.1 / 4.0±0.2 | 31±4 / 1.69 | |
| AFGL 1977 | 1999 April | 990±90 / 40 | 2.5±0.5 / 6.0±0.8 | 68±19 / 0.65 | |
| AFGL 2135 | 2001 June | 740±370 / 270 | 3.2±4.2 / 9.4±65.7 | 16±40 / 5.04 | |
| AFGL 2252 | 1998 June | 1110±140 / 110 | 1.6±0.2 / 5.1±0.5 | 48±10 / 0.32 | |
| AFGL 2252 | 1999 April | 1300±200 / 230 | 2.8±1.4 / 9.4±5.0 | 165±226 / 3.29 | |
| AFGL 2513 | 1998 September | 1500±150 / 40 | 1.9±0.2 / 1.7±0.9 | 53±7 / 0.57 | |
| AFGL 2513 | 1999 July | 1110±400 / 200 | 1.2±0.5 / 3.1±1.0 | 18±14 / 0.30 | |
| AFGL 2686 | 1998 September | 1110±270 / 310 | 2.8±0.5 / 5.3±1.1 | 53±24 / 1.85 | |
| AFGL 2686 | 1999 July | 820±60 / 60 | 3.2±0.2 / 5.1±0.3 | 19±4 / 1.02 | |
| AFGL 4211 | 2000 June | 880±60 / 30 | 3.7±0.7 / 6.7±0.3 | 85±9 / 0.73 | |
| AFGL 4211 | 2001 June | 850±170 / 80 | 4.2±0.9 / 6.1±3.7 | 71±13 / 3.20 | |
| IRAS 15148−4940 | 2001 June | 940±340 / 170 | 0.23±0.46 / 4.6±0.2 | 40±4 / 2.47 | |
| IY Hya | 1999 April | 960±140 / 110 | 0.46±0.12 / 4.2±0.1 | 33±2 / 0.25 | |
| LP And | 1998 September | 880±60 / 70 | 3.6±0.5 / 4.8±0.5 | 43±8 / 1.49 | |
| LP And | 1999 July | 820±60 / 60 | 3.6±0.5 / 4.8±0.6 | 44±12 / 1.00 | |
| LP And | 1999 January | 880±90 / 30 | 3.2±0.5 / 6.7±1.0 | 85±27 / 1.67 | |
| RV Aqr | 1999 July | 1500±30 / 280 | 0.46±0.23 / 5.4±0.4 | 55±15 / 1.09 | |
| RV Aqr | 1998 June | 1190±310 / 150 | 0.23±0.46 / 5.1±0.7 | 48±2 / 0.23 | |
| v1899 Cyg | 1998 June | 740±60 / 60 | 2.3±0.5 / 2.0±0.3 | 7.5±1.8 / 0.53 | |
| V Cyg | 1998 June | 1270±320 / 320 | 0.69±0.23 / 6.6±0.7 | 83±3 / 3.02 | |
| V Cyg | 1999 April | 1160±210 / 110 | 0.23±0.23 / 9.6±0.3 | 174±11 / 0.21 | |
| V Cyg | 2001 June | 1270±140 / 140 | 0.46±0.23 / 10.6±1.6 | 217±70 / 0.24 | |

*This star has two regions which meet our 1σ criteria for a best fit. The particular values shown were chosen for consistency; see the appropriate figure for more details.

Note. The horizontal line separates oxygen rich (top) from carbon rich (bottom).

the SED, we also used including V-band magnitudes in our fit with a very low weight to ensure that the optical depths were not too low (important especially when for objects without photometry in all three near-IR wavelength bands). When calculating the $\chi^2$ for the visibility curves, we adopted the following procedure. Because the $y$-intercept of our observed visibility data can fluctuate ±5 per cent due to seeing calibration, we normalized each visibility to 1.0 at zero baseline before fitting. Also, we weighted the visibility points so that the SED and the visibility data were separately given equal weight in the final reduced $\chi^2$. We purposefully chose not to include longer wavelength SED measurements, such as IRAS data, in our fitting. By fitting only to near-IR photometry and near-IR spatial data, we can isolate and only probe dust emitted within the last few decades. This allows us to keep the model as simple as possible and enhances the validity of our assumption of constant mass-loss rate (i.e. $\rho \propto r^{-3}$).

Once the grid calculation over inner dust temperature $T_{\text{dust}}$ and $\tau_{2.2\,\mu m}$ was completed, the $\chi^2$ surface was used to estimate the best-fitting parameters. The uncertainty estimates were produced by considering the region where the reduced $\chi^2$ was less than 2, a highly conservative criterion that reflects the highly correlated errors in our data sets. In the cases where the best-fitting $\chi^2$ is

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above 1, we scaled the $\chi^2$ results by the best-fitting value before estimating the parameter uncertainties. The best-fitting parameters and their uncertainties are compiled in Table 8.

In addition to providing the fitting results in a tabulated form, we also include here a series of figures which graphically represent the new data, modelling results, and the $\chi^2$ surface in our grid. These plots can be found in each of Figs 1–20. The first panel in each figure contains the observed near-IR photometry and best-fitting model SED. The second panel in each figure contains the multi-wavelength visibility curves averaged azimuthally along with the model curves. Finally, the third panel shows the $\chi^2$ surface in the ($T_{\text{dust}}$, $\tau_{2\mu m}$) plane. We have grouped all the epochs for the same object together so that one can see the self-consistency in the derived dust shell parameters – indeed, consistent dust shell properties were recovered when fitting to different epochs, despite large changes in the central star luminosity due to pulsations.

One of the most important results to take away from these panels is that we clearly break the standard degeneracy between dust temperature and optical depth. This is because of our new spatial information – by measuring the sizes of the dust shell at various wavelengths, we can simultaneously constrain the temperature and optical depth. In the past, one typically had to choose an inner dust temperature based on physical arguments concerning the dust condensation temperatures of various dust species. Here, we see that the inner dust temperature can be constrained independently from other parameters and the implications are discussed further in the following section.

While the simultaneous fits to the near-IR SED and visibility data were generally acceptable, we found that the fits to the shortest wavelength visibility data at the $H$ band were systematically worse.
Asymmetry of Dust Shells for AGB Stars

Since this band is most sensitive to scattering by dust, we explored modified dust distributions, especially using larger grains: we did not find systematic improvements to the fits by altering dust size distribution from MRN or by using other dust constants.

4 DISCUSSION

Our survey provides the first constraints on the asymmetry of the dust shells for such a large sample of dust-enshrouded AGB stars. We found that 4 out of 7 M-stars and 5 of 13 C-stars showed evidence of dust shell asymmetries, with dust shell elongations between 10 and 40 per cent. While this level of asymmetry may sound mild, it actually (quantitatively) compares to the level of asymmetry that would be expected for the most asymmetric dust shells known if placed at 1 kpc. For instance, we know that IRC +10216 (Tuthill et al. 2000a) and CIT 6 (Monnier, Tuthill & Danchi 2000) have dramatic global asymmetries in their dust shell, detailed imaging made possible by virtue of their proximity. If we placed these targets farther away, we would not be able to image the detail but they would appear ~20 per cent elongated, similar to the...
Figure 13. Best-fitting plots for AFGL2686. See the caption of Fig. 1.

Figure 14. Best-fitting plots for AFGL4211. See the caption of Fig. 1.

Figure 15. Best-fitting plots for IRAS15148−4940. See the caption of Fig. 1. We chose the lower-right region as the best-fitting region because in all other cases of multiple good-fitting regions, the one at low tau and high dust temperature was the consistent region.

degree observed here in 45 per cent of our sample. For CIT 3, we confirm the asymmetries seen by Hofmann et al. (2001) and note that Vinković et al. (2004) showed that the 20 per cent elongation could be explained by a bipolar outflow. That said, clumpy dust formation (Fleischer, Gauger & Sedlmayr 1992) might also cause stochastic variations in the inner dust shell geometry that could appear as short-lived elongations. Mid-IR observations with long-baseline interferometers [e.g. ISI (Infrared Spatial Interferometer), VLTI-MIDI (Very Large Telescope Interferometer-mid Infrared Interferometric Instrument)] should focus on these targets to determine the nature of the asymmetries. In addition, long-term monitoring of these dust shells will help settle debates concerning when the environments of evolved stars develop large-scale asymmetries commonly revealed in the later planetary nebula stage. For instance, a long-term asymmetry in a constant position angle (as judged by linear polarization or spatially resolved data) would be a sign of a global bipolar mass-loss asymmetry and not just weather.

Figure 16. Best-fitting plots for IY Hya. See the caption of Fig. 1.

Figure 17. Best-fitting plots for LP And. See the caption of Fig. 1.

Figure 18. Best-fitting plots for RV Aqr. See the caption of Fig. 1.
In order to look at dust shell properties for our full sample, we have plotted the inner edge dust temperature $T_{\text{dust}}$ versus total dust shell optical depth $\tau_{2.2\mu m}$ for all our targets. Fig. 21 shows that these results split into O-rich and C-rich dust types. For K-band optical depths below 2, we find the sublimation temperature of $T_{\text{sub}}$(silicates) = 1130 $\pm$ 90 K and $T_{\text{sub}}$(amorphous carbon) = 1170 $\pm$ 60 K, both somewhat lower than expected from laboratory measurements (Lodders & Fegley 1999) and vastly below temperatures inferred from the inner edge of YSO discs ($\sim$1800 K; Tannirkulam et al. 2008; Benisty et al. 2010). One component to the observed lower dust temperature could be due to the fact that the central star varies in luminosity by about a factor of 2 during the pulsation cycle and we see the dust cooler than the condensation temperature during phases away from maximum light.

The $T_{\text{dust}}$ versus optical depth $\tau_{2.2\mu m}$ diagram (Fig. 21) also shows no statistically significant difference between O-rich and C-rich dust types, counter to expectation of higher temperatures for C-rich dust (Lodders & Fegley 1999). We recognize that our simple dust shell modelling may not lead to accurate estimates of the dust sublimation temperature if the inner dust formation environment radically departs from a power law density distribution, perhaps due to pulsations, time-scale for dust formation or multiple dust species. Interestingly though these concerns would likely affect C-rich and O-rich shells similarly and so the lack of a clear difference in sublimation temperatures between these dust types appears robust.

The other important feature of Fig. 21, $T_{\text{dust}}$ versus optical depth $\tau_{2.2\mu m}$, is that the apparent temperature at the inner edge of the dust shell gets lower and lower with increasing optical depths above 2. This appears true for both C-rich and O-rich shells. Here we do not believe we are seeing an actual reduction in the dust sublimation temperature, but rather a change in the temperature profile in the inner dust formation zone due to a breakdown in the assumption of a spherically symmetric $r^{-2}$ density power law. We have ample evidence that dust formation is clumpy, as has been imaged in great detail for IRC +10216 (Tuthill et al. 2000a), but these clumps have been shown to have a relatively weak effect on the temperature structure for low optical depths. Next we further explore how a clumpy dusty environment could change the temperature profile of the dust shell when the individual clumps themselves become optically thick to the stellar and even hot dust radiation field.

Clumpy structures are seen to evolve in 2D models of dust shells due to self-amplifying density perturbations (e.g. Woitke, Sedlmayr & Lopez 2000). First optically thick dust regions form and these regions cast shadows on the dust behind them. Consequently, the temperatures decrease by hundreds of kelvins and this allows for a higher rate of dust formation in these shadow regions. Scattering and re-emission of light by the optical thick regions increases the intensity of radiation between them and eventually the light escapes through the optically thin regions in between the optically thick regions. Thereupon, the temperature within the optically thin regions increases, which decreases the rate of dust production. These processes thus amplify the initial homogeneities until large-scale clumpy structures start to form, such as ‘dust fingers’ (Woitke & Niccolini 2005). Indeed, Woitke & Niccolini (2005) did see average dust temperatures to be reduced due to these opacity effects but at much weaker level than we see in Fig. 21. Realizing that our data reveal a strong effect only at $\tau$’s several times larger than probed by
Woitke & Niccolini (2005), we suggest that dust shadowing effects get dramatically stronger when individual clumps become optically thick to both stellar radiation and hot dust emission. A 3D radiative transfer calculation of a dusty dust shell could validate or disprove this explanation.

In conclusion, our large sample of spatially resolved dust-enshrouded stars has led to new insights into the late stages of AGB star evolution. We find levels of dust shell elongations that point to significant asymmetries in nearly half of our targets. Our spatial and SED data combined have eliminated some model degeneracies, and we now have the best constraints on the actual sublimation temperatures for dust forming in these outflows, finding lower temperatures than expected from terrestrial experiments and not confirming the large difference expected between carbon-rich and silicate-rich dust. Lastly, we discovered a systematic change in the temperature profile for inner-most dust regions when the dust shell optical depth rises above $\tau_{2.2 \mu m} > 2$. This observed lowering of the central dust temperatures could be naturally explained as a consequence of shadowing caused by clumpy dust formation on spatial scales smaller than our angular resolution, but other possibilities should be further explored as well.

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