Near-infrared polarimetry and modelling of the dusty young PN IRAS 19306+1407.

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ABSTRACT
We present near-infrared polarimetric images of the dusty circumstellar envelope (CSE) of IRAS 19306+1407, acquired at the United Kingdom Infrared Telescope (UKIRT) using the UKIRT 1-5 μm Imager Spectrometer (UIST) in conjunction with the half-waveplate module IRPOL2. We present additional 450 and 850 μm photometry obtained with the Sub-mm Common User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT), as well as archived Hubble Space Telescope (HST) F606W- and F814W-filter images. The CSE structure in polarized flux at J- and K-bands shows an elongation NNE-SSW with two bright scattering shoulders NW-SE. These features are not perpendicular to each other and could signify a recent ‘twist’ in the outflow axis. We model the CSE using an axisymmetric light scattering (ALS) code to investigate the polarization produced by the CSE, and an axisymmetric radiation transport (DART) code to fit the SED. A good fit was achieved with the ALS and DART models using silicate grains, 0.1-0.4 μm with a power-law size distribution of $a^{-3.5}$, and an axisymmetric shell geometry with an equator-to-pole contrast of 7:1. The spectral type of the central star is determined to be B1I supporting previous suggestions that the object is an early PN. We have constrained the CSE and interstellar extinction as 2.0 and 4.2 mag respectively, and have estimated a distance of 2.7 kpc. At this distance the stellar luminosity is $\sim 4500$ $L_\odot$ and the mass of the CSE $\sim 0.2$ $M_\odot$. We also determine that the mass loss lasted $\sim 5300$ yrs with a mass-loss rate of $\sim 3.4 \times 10^{-5} M_\odot$ yr$^{-1}$.

Key words: stars: AGB and post-AGB – stars: circumstellar matter – infrared: stars – stars: individual (IRAS 19306+1407) – stars: mass loss – techniques: polarimetric.

1 INTRODUCTION
Post-asymptotic giant branch (post-AGB) stars are luminous ($10^3$-$10^4$ $L_\odot$) evolved stars with initial masses in the range 0.8-8 $M_\odot$ (see Van Winckel 2003, for a general review). At the end of the AGB phase, mass-loss rates can peak at over $10^{-4}$ $M_\odot$ yr$^{-1}$ before dropping dramatically, as the star enters its post-AGB evolution (e.g. Schönberner 1983), creating detached envelopes of gas and dust. These dusty circumstellar envelopes (CSEs) are then visible at optical and near-infrared wavelengths as protoplanetary nebulae (PPN; Kwok 1993). A seemingly ubiquitous feature of PPN is their lack of spherical symmetry, with many having a bipolar or point-symmetric structure. Notable and well-studied examples are the Egg Nebula (AFGL 2688; Sahai et al. 1998) and the Red Rectangle (AFGL 915; Cohen et al. 2004). Optical and near-infrared surveys of PPN have shown that in all cases where a CSE is detected then it appears asymmetric in some way (e.g. Ueta, Meixner & Bobrowsky 2000; Gledhill et al. 2001). Possible mechanisms for the shaping of PPN usually involve interaction of the mass-losing star with a binary companion, and have been reviewed by Balick & Frank (2002).

Imaging polarimetry is a differential imaging technique, which is well-suited to the study of CSEs surrounding post-AGB stars. The technique discriminates between the faint but polarized scattered light from the PPN and any bright unpolarized emission from the central star. This enables the imaging of circumstellar material that would normally be lost under the wings of the stellar point spread function (PSF), thereby obtaining information on the dust distribution close to the central source. Imaging polarimetric surveys of post-AGB stars using the UK Infrared Telescope have detected scattered light from PPN around 34 stars, and all of these PPN were found to be asymmetric in some way (Gledhill et al. 2001; Gledhill 2002). Higher spatial resolution polarimetry using the Hubble Space Telescope (HST)
has enabled more detailed studies of the morphology of PPN, as well as providing constraints on dust grain properties in these systems, and has revealed point-symmetries, jets and multi-lobed structures (e.g. Ueta, Murakawa & Meixner [2007], Su et al. [2003]).

In this paper, we examine IRAS 19306+1407 (GLMP 923), which has IRAS colours typical of a post-AGB star with a cold CSE (Omont et al. [1993]). Radio and millimetre surveys for molecular emission have failed to detect OH or H2O masers (Lukel [1989]) or CO emission (Arquilla et al. [1984], Likkel et al. [1991]). However, the object shows a number of dust spectral features. Hrivnak, Volk & Kwok (2000) present ISO spectroscopy showing emission features at 6.3, 7.8 and 10.7 μm, with a “probable” feature at 3.3 μm, and compare these features to the unidentified infrared (UIR) bands at 3.3, 6.2 and 7.7 μm, commonly attributed to polycyclic aromatic hydrocarbon (PAH) molecules (Allamandola, Tielens & Barker [1989]).

Given that the mid-infrared spectral features are similar to those seen in hot carbon-rich PN, Hrivnak et al. (2000) suggest the presence of silicate emission at 11, 19 and 23 μm, with line width of 8.6 and 11.2 μm, indicating a fast outflow. Optical spectroscopy shows a broadened Hα emission line with line width of ~2300 km s⁻¹ indicating a fast outflow (Sabai & Sánchez Contreras [2004], as well as H and [NII] emission, leading (Kelly & Hrivnak [2003]) to suggest a spectral type of approximately B0 for the star. A number of H₂ emission lines are seen in the K-band, with line ratios suggesting a mix of radiative and shock excitation (Kelly & Hrivnak [2003]). Imaging through a narrow-band H₂ filter, centred on the 2.122 μm line, shows that the H₂ emission has a ring-like structure with evidence for bipolar lobes extending perpendicular to the ring (Volk, Hrivnak & Kwok [2004]).

We present the first near-infrared polarimetric images of the dusty CSE of IRAS 19306+1407, showing the structure of the envelope in scattered light. We also present new sub-millimetre photometry and archived HST images. The observations are interpreted using 2-dimensional (axisymmetric) light scattering and radiation transport models.

### Table 1. Summary of photometry for IRAS 19306+1407 for HST (using Vega zero points), UKIRT and SCUBA observations, including integration time (Int.) and the extent (Size) of the semi-major and minor axes of the aperture used in photometry. The PA angle of photometry aperture is equal to 18° (E of N).

| Band   | Magnitude | Flux   | Int. | Size          |
|--------|-----------|--------|------|---------------|
| F606W  | 13.81 ± 0.03 | 9.5 ± 0.3 | 300  | 3.2 × 2.0     |
| F814W  | 12.45 ± 0.02 | 26.1 ± 0.5 | 50   | 3.2 × 1.9     |
| F110W  | 11.18 ± 0.04 | 51.5 ± 0.8 | 237.6 | 3.9 × 2.4     |
| F160W  | 10.29 ± 0.12 | 48.4 ± 2.2 | 237.6 | 3.9 × 2.4     |
| 450W   | -          | 49.9 ± 38.7 | 1334† | -             |
| 850W   | -          | 14.1 ± 3.7  | 1334† | -             |

Notes: central wavelengths at *0.5888μm (Broad Hα), *0.8115μm (Johnson I), †1.25μm, ‡2.2μm, §450μm and §850μm; and 1 inclusive of observational overheads.

Photometric standards, FS 147 (J) and FS 141 (K), were used to flux calibrate the data giving J=11.18 ± 0.04 and K=10.29 ± 0.12.

For these observations, the focal plane polarimetry mask was removed, so that a 512 by 512 pixel sub-array of the UIST detector could be used. This enabled faster read-out times and exposures of less than 1 second, so that observations of bright sources could be made without the risk of saturation. This configuration of UIST resulted in the overlapping of the o- and e-beams produced by the Wollaston prism and a final analysis area of 20 by 60 arcsec. The Wollaston prism splits each star into an e- and o-component separated by 20 arcsec, so that any star in the field lying more than 10 arcsec along the prism dispersion axis from the target will only have one component in the analysis area. Since both e- and o-beams are required to correctly calculate the Stokes intensities I, Q and U, these offset stars appear as highly polarized artefacts in the reduced data, and are marked as such on Fig. 1. As the prism dispersion varies slightly with wavelength, this results in an apparent shift of the artefact stars between the J- and K-bands.

The J- and K-band polarimetric results are shown in Fig. 1. The total intensity images are shown in Fig. 1(a) and (c), superimposed with polarization vectors, and show the centrally peaked nature of the source. The object is clearly extended, relative to the 0.5 arcsec seeing FWHM, with faint emission detected out to a radius of approximately 3 arcsec. The lowest contour in both filters is 3 times the sky noise and in the I1 image, shows that the faint emission is elongated in a NNE/SSW direction. Details of contour levels are given in the Figure caption. It is possible that a similar extension is present in the I2 image, but confusion due to the presence of the artefact stars makes this uncertain.

The polarized flux, produced by light scattering from out using STARLINK1 applications. A bad pixel mask was created using ORACDR and chopped to 512 by 512 pixels. The standard subtraction of dark frames and flat fielding were carried out using CCDPACK. A 3D cube consisting of the I, Q and U Stokes images, was produced using POLKA from the POLPACK suite, and this was then used to derive the per cent polarization, polarized flux and polarization angle. A more detailed description of dual-beam polarimetry and the data reduction techniques is given by Berry & Gledhill (1998).

1 Available from www.starlink.ac.uk
Near-IR polarimetry and modelling of IRAS 19306+1407.

Figure 1. High resolution images are available at [http://star-www.herts.ac.uk/~klowe/](http://star-www.herts.ac.uk/~klowe/) The J- and K-band observations are displayed at the top and bottom of the figure respectively. These images have been scaled logarithmically. The total intensity (I) is displayed in sub-figures (a) and (c) with overlaid polarization vectors (pol). Sub-figures (a) and (c) are scaled between 20 and 13 mag arcsec$^{-2}$. The lowest outer contour levels are 19 and 18 mag arcsec$^{-2}$ and separated by 1 mag arcsec$^{-2}$ for (a) and (c) respectively. The polarized flux (IP) images (b) and (d) are scaled between 20 to 16 mag arcsec$^{-2}$ and 19 to 16 mag arcsec$^{-2}$ respectively. The lowest outer contours are 19 (b) and 18 (d) mag arcsec$^{-2}$ and separated by 0.5 mag arcsec$^{-2}$.

dust grains, is shown in Fig. 1 (b) and (d). In both filters, the central region appears elongated along a PA 136$^\circ$ East of North, with two bright shoulders of emission either side of the star. At J (IP$_J$ image) this structure is embedded within fainter more extended emission orientated at 18$^\circ$ East of North, seen in the lowest three contours (the lowest contour is at 1.5 times the sky noise). This faint extension is not as apparent in the K-band polarized flux image (IP$_K$), which is approximately 1 mag arcsec$^{-2}$ shallower than the J-band data. The NW shoulder is brighter than the SE shoulder, particularly apparent in the IP$_J$ image. Similar morphology has been observed in polarised flux in a number of other PPN. [Gledhill et al. (2001)] found bright arc-like structures on either side of the star in IRAS 17436+5003 as well as shoulder-like features in IRAS 19500-1709 and more ring-like features in IRAS 22223+4327 and 22272+5435. They interpreted these structures in terms of scattering from the inner surfaces of a detached axisymmetric shell, with an equatorial density enhancement, and classified these objects as “shell-type” objects. The arcs in IRAS 17436+5003 were later fully resolved in mid-infrared imaging of thermal emission from the dust [Gledhill & Yates (2003)] and successfully modelled using an axisymmetric dust distribution based on that of [Kahn & West (1983)]. Further evidence for arcs and shoulders is seen in polarized flux images of IRAS 06530-0213, 07430+1115 and 19374+2359 [Gledhill (2005)] and was interpreted using light-scattering in a Kahn & West density distribution. We therefore interpret the polarized flux shoulders seen around IRAS 19306+1407 in the same way, and suggest that they result from increased scattering at the in-
ner boundary of a detached shell with an equatorial dust density enhancement.

The polarization vectors shown in Fig. 1 (a) and (c) are binned over 0.36 × 0.36 arcsec (3 × 3 pixels) and have a signal-to-noise threshold of 2 in per cent polarization. The vector pattern appears approximately centro-symmetric in both filters, indicating isotropic illumination by a central source. The maximum per cent polarization is 15 ± 6 and 10 ± 4 at J- and K-bands respectively (Table 2). These values are lower limits to the intrinsic polarization, since in these observations it has not been possible to correct for dilution of the polarized flux by the unpolarized light from the central star.

### 2.2 Hubble Space Telescope observations and results

We have obtained archived HST images for IRAS 19306+1407 observed on 2003 September 8 (proposal ID: 9463). The observations were obtained with the Advanced Camera for Surveys (ACS), in conjunction with the High Resolution Channel (HRC), using F606W- and F814W-filters with pivotal wavelengths of 5888 and 8115 Å respectively. The images were reduced using the On-the-Fly Reproprocessing of HST Data (OTFR), which produces a cosmic-ray cleaned, calibrated, geometrically corrected mosaic image. Aperture photometry was performed using GAIA, using the Vega zero points, and obtained magnitudes of 13.81 ± 0.03 and 12.45 ± 0.02 for F606W and F814W respectively (Table 2).

The reduced F606W and F814W images are shown in Fig. 2 (a) and (b). Fig. 2 (c) shows the F606W image superimposed with contours of J-band polarized flux from Fig. 1 (b). The object is clearly bipolar in the F606W image, and the curved edges of bipolar cavities, extending for 3 to 4 arcsec from the source, can be seen. The orientation of the bipolar axis, at PA 18 deg, is aligned with the J-band elongation in total and polarized intensity seen in Fig. 1 (a) and (b). The bipolar structure appears to be surrounded by a faint, more spherically symmetric halo, seen in both HST filters, and this corresponds in extent to the outer contours in Fig. 1 (a) and (c). The polarized flux shoulders, at PA 136 deg, are not perpendicular to the major axis of the nebula and this is clearly seen in Fig. 2 (c). This non-orthogonality in the two axes will be discussed further in Section 4.

The southern bipolar lobe appears to be the brighter of the two in both HST filters, which could indicate that the major axis is slightly inclined to the plane of the sky.

### 2.3 Sub-millimetre observations and results

Observations were made on 2005 January 8 using the Sub-millimetre Common User Bolometer Array (SCUBA) at the 15 m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawai‘i. The SCUBA observations were made simultaneously at 450 and 850 µm in photometry mode using a jiggle pattern. The 450 and 850 µm photometry data were reduced using the SURF package within the STARLINK suite. The sky opacity was corrected using the Caltech Sub-millimetre Observatory (CSO) tau relationship. Flux calibration was performed using Mars, inclusive of a maximum ±5 per cent error due to the orientation of Mars’ poles relative to the Earth and Sun. IRAS 19306+1407 was detected at 450- and 850-µm at > 3σ and > 7σ respectively inclusive of calibration errors. The fluxes obtained (Table 3) for F1450 and F850 are 49.9 ± 38.7 mJy and 14.1 ± 3.7 mJy within a beam size of 7.5 and 14 arcsec respectively.

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2 Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Institute. STScI is operated by the association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555.

3 [http://star-www.herts.ac.uk/~klowe/](http://star-www.herts.ac.uk/~klowe/)

4 Using the revised 2000 October 25 relations
3 MODELLING THE CSE

3.1 Model details

To investigate the dusty CSE around IRAS 19306+1407, we use modified versions of the Ménard (1989) axisymmetric light scattering (ALS) code to produce Stokes $I$, $Q$, $U$ images and the axisymmetric radiative transfer (DART) code (Lister & Rowan-Robinson 1996) to model the SED. Both codes have previously been used to model the CSEs of post-AGB stars. (Gledhill & Yates 2003) used DART to simulate multi-wavelength mid-infrared imaging observations of IRAS 17436+5003, in which an axisymmetric shell was resolved. To simulate the axisymmetry, these authors used a simple dust density formulation from Kahn & West (1983) which was found to successfully reproduce all of the axisymmetric features, including the offset location of the brightness peaks seen in the data, which was found to be due to the inclination of the system to the plane of the sky. Gledhill (2005) have used the ALS code to produce generic light scattering models of PPN at varying optical depth and also find that a Kahn & West density model provides a good representation of the observations with a minimum number of model parameters. It is important that the dust density model uses a minimum number of parameters whilst achieving an adaptable axisymmetric geometry, so that there is a better chance of each parameter being observationally well constrained. More complex dust density formulae have been used (e.g. Meixner et al. 2002), which incorporate the presence of AGB and superwind mass loss histories, but require more parameters (twice as many in the case of Meixner et al. 2002). These models result in morphologies that are qualitatively similar to our simpler models, but are unlikely to be well constrained by our observations. In both the ALS and DART models we therefore use a simpler density profile from Kahn & West (1983) to model an axisymmetric shell, whilst recognising its limited ability to reproduce more complex morphologies:

\[
\rho(r, \theta) = \rho_0 \left( \frac{r}{r_{\text{in}}} \right)^{-\beta} (1 + \epsilon \sin^\gamma \theta),
\]

where $\rho_0$ is the density at the pole ($\theta = 0^\circ$) at the inner radius, $r_{\text{in}}$, and $\beta$ specifies the radial density distribution. The azimuthal density distribution is determined by parameters $\epsilon$ and $\gamma$, which specify the equator-to-pole density ratio ($1 + \epsilon$) and the degree of equatorial enhancement, respectively. An increase to $\gamma$ flattens the density distribution, creating a more toroidal structure.

All parameters in Equation 1 are optimized in the model, apart from $\beta$, which is fixed at a value of 2 due to a limitation of the DART code, corresponding to constant mass-loss rate and expansion velocity for the AGB wind. The ALS density profile includes an extra parameter, that restricts the axisymmetry to within a radius, $r_{\text{sw}}$, modifying Equation II to:

\[
\rho(r, \theta) = \rho_0 \left( \frac{r}{r_{\text{in}}} \right)^{-\beta} \quad \text{when} \quad r > r_{\text{sw}}.
\]

A power law size distribution is used with spherical grains of radius $a$, between a minimum and maximum grain size of $a_{\text{min}}$ and $a_{\text{max}}$ respectively, and a power-law index, $q$:

\[
n(a) \propto a^{-q} \quad \text{for} \quad a_{\text{min}} \leq a \leq a_{\text{max}}.
\]

The inclination of the symmetry axis to the plane of the sky is not known. As mentioned in Section 2.2 the southern bipolar lobe appears slightly brighter than the northern one in HST imaging (Fig 2), which could indicate a small inclination to the plane of the sky. Although the near-infrared images appear consistent with zero inclination (e.g. they are similar to edge-on axisymmetric shell models shown in Gledhill 2005), we consider the inclination angle to be a free parameter and allow it to vary in steps of 10 deg.

The overall chemistry of the system is uncertain. The results from Hrivnak et al. (2000) suggest a C-rich nature based on emission features consistent with C-rich PNe. Hodge et al. (2004) re-evaluated the mid-infrared spectra and classified IRAS 19306+1407 as “UIR features coupled with emission from crystalline silicates” suggesting a dual chemistry nature. The dust species that have been considered in our models are amorphous carbon (amC), silicon carbide (SiC) and Ossenkopf cold silicates, and we have obtained the optical constants from Preibisch et al. (1993), Péroux (1988) and Ossenkopf et al. (1992) respectively.

We ran a total of over 150 ALS and over 300 DART models to create a model grid for the free physical parameters (Table 3). The minimum and maximum grain sizes were investigated from 0.005 to 1 $\mu$m, with a variable grain size spacing typically 0.005 to 0.02 $\mu$m. The grain size power law index was varied between 3.0 to 6.0 at increments of 0.5. The radial density fall off exponent is fixed at $\beta = 2$ and cannot not be varied. The bin widths for the CSE parameters, common to both models are 1, 2, 10$^0$ and 0.1$\times$10$^{-2}$ for the equator-to-pole contrast ($\epsilon$), equatorial density enhancement ($\gamma$), inclination angle ($\theta$) and the ratio of the inner-to-outer radii ($r_{\text{in}}/r_{\text{out}}$) respectively. The stellar temperature, $T_*$, was investigated using a series of Kurucz models $^5$ with solar metallicities and temperatures separated by 1000 K.

The ALS code is used to determine the best-fitting envelope parameters based on the morphology, azimuthal profiles in polarized flux and radial profiles of the percentage polarization and total intensities. The ALS code is additionally used to constrain the dust grain size by generating polarization information. The ALS estimate of the grain size is an important input to the DART calculations, which would otherwise suffer from a degeneracy between grain size and outer CSE radius, both of which strongly influence the long-wavelength tail of the SED. The optical depths at 0.55, 1.2 and 2.2 $\mu$m are also derived from the ALS model and subsequently inserted into the DART model. The DART model fits to the SED are used to constrain the temperature of the central star, inner-to-outer and stellar-to-inner radii ratios. The two codes were used to iteratively produce a convergent model.

3.2 Model results

3.2.1 ALS model

Before the raw model images can be compared with the polarimetric observations, they must be smoothed to mimic the effect of the atmosphere and telescope. We find that a simple Gaussian filter is unable to reproduce the wings of

$^5$ http://kurucz.harvard.edu/grids.html
Figure 3. High resolution images are available at [http://star-www.herts.ac.uk/~klowe](http://star-www.herts.ac.uk/~klowe). The 1.2- and 2.2-µm smoothed model images of IRAS 19306+1407 are displayed at the top and bottom of the figure respectively. These images are rotated to a PA of 136° to mimic the observed data. As with the observed images they have been scaled logarithmically. The total intensity (I) is displayed in sub-figures (a) and (c) with overlaid polarization vectors (pol) and polarized flux is shown in (b) and (d). The model images have been normalised at the same levels as the observed images: (a) and (c) are scaled between 20 and 13 mag arcsec$^{-2}$ with lowest outer contour levels at 19 and 18 mag arcsec$^{-2}$, respectively, separated by 1 mag arcsec$^{-2}$; (b) and (d) are scaled between 20 to 16 mag arcsec$^{-2}$ and 19 to 16 mag arcsec$^{-2}$ respectively with lowest outer contours at 19 (b) and 18 (d) mag arcsec$^{-2}$, separated by 0.5 mag arcsec$^{-2}$.

the PSF effectively, which is essential since the PSF wings have a critical effect on the percentage polarization in the envelope where the intensity is low, at $r \gtrsim r_{in}$. To obtain a more realistic fit we use a Moffat filter profile:

$$M(r) \propto \left[1 + \left(\frac{r}{\alpha_{mof}}\right)^2\right]^{-\beta_{mof}},$$

where $r$ is radius from the source and $\alpha_{mof}$ and $\beta_{mof}$ are fitting parameters [Moffat 1969]. The Moffat parameters were calculated by fitting to the PSF of a bright field star (Table 4) and their uncertainties were estimated by examining the fit to the remaining field stars. The filter was then applied to the raw ($I$, $Q$ and $U$) model images, which were then combined to obtain polarized flux and per cent polarization values.

The resulting best-fitting smoothed model is shown in Fig. 3 and the parameters used are displayed in Table 3. The model reproduces the centrosymmetric polarization pattern and the observed degrees of polarization in the $J$- and $K$-bands. The polarized flux images show the shoulders seen in the observations, due to the enhanced scattering at the inner edges of the axisymmetric shell, where the dust density is greatest. In Fig. 1, the observed polarized flux images show a peak of emission at the location of the star. Any mis-
Near-IR polarimetry and modelling of IRAS 19306+1407.

Figure 4. High resolution images are available at [http://star-www.herts.ac.uk/~klowe/](http://star-www.herts.ac.uk/~klowe/). Left: Azimuthally averaged radial profiles of the normalised total intensity. Centre: Azimuthally averaged radial profiles of the per cent polarization. Right: Radially averaged azimuthal profiles of the normalised polarized intensity. In all cases, the J- and K-band data are displayed as squares and triangles respectively, with 3σ error bars, and the 1.2- and 2.2-μm smoothed model data are displayed as solid and dashed curves respectively.

alignment of the bright, centrally-peaked images during the data reduction stages will lead to a residual polarization at this location. Since the polarized flux peak is narrower than the seeing disc size, we cannot treat it as significant. We do not see polarized emission from the location of the star in the model images, since forward-scattered light (i.e. scattering angles close to zero) is strongly depolarized. Higher spatial resolution observations will be required to investigate the polarization within 0.2 arcsec of the star. If there is significant polarized emission from this region, then an additional dust component would be required in the model.

The fit was assessed by comparing the full grid of ALS models to the polarimetric observations. In particular, the radial and azimuthal profiles of the smoothed model images and the observations were compared and the profiles for the best-fit model are shown in Fig. 4. The total intensity image radial profile fit (Fig. 4 left) provides a check on the level of smoothing, and shows an excellent fit to the observed intensity profile at both wavelengths. The fit to the radial distribution of per cent polarization (Fig. 4 centre) allows us to constrain the dust grain parameters and optical depth. The maximum degree of polarization produced by the model is very sensitive to the grain size distribution so we consider that the grain size is well constrained. The radial distribution of per cent polarization depends strongly on the optical depth (and hence the dust density), since this determines the surface brightness of the CSE relative to the unpolarized light from the smoothed PSF. We determine an optical depth of 0.68 and 0.11 at J and K respectively, so that the CSE is optically thin in the near-infrared. The axisymmetry parameters, ɛ and γ are determined by comparing azimuthal
Table 3. The CSE and dust grain parameters for the best-fitting ALS and DART models for IRAS 19306+1407.

| Parameter                  | Value         | Description                          |
|----------------------------|---------------|---------------------------------------|
| Dust grain parameters      |               |                                       |
| Ossenkopf                  |               |                                       |
| Cold Silicates            | 1.0 ± 0.01    | Number fraction                       |
| $a_{\text{min}}$ (µm)      | 0.10 ± 0.01   | Minimum grain radius                  |
| $a_{\text{max}}$ (µm)      | 0.40 ± 0.01   | Maximum grain radius                  |
| $q$                        | 3.5 ± 0.5     | Grain size power law index            |
| Common envelope model parameters |           |                                       |
| $\beta$                    | 2             | Radial density fall off               |
| $\epsilon$                | 6 ± 1         | Equator-to-pole density contrast      |
| $\gamma$                  | 5 ± 2         | Equatorial density enhancement       |
| $\theta$ (deg)             | 0 ± 10        | Inclination angle (from equator)     |
| $r_{\text{in}}/r_{\text{out}}$ (10$^{-2}$) | 7 ± 1          | Inner-to-outer radius ratio           |
| ALS model parameters       |               |                                       |
| $\tau_1$ ($10^{-1}$)       | 6.78 ± 0.05   | Optical depth at 1.2 µm               |
| $\tau_2$ ($10^{-1}$)       | 1.13 ± 0.01   | Optical depth at 2.2 µm               |
| $r_{\text{sw}}/r_{\text{in}}$ | 2.0 ± 0.5     | Super-wind to inner radius ratio      |
| DART model parameters      |               |                                       |
| $T_*$ (10$^3$ K)            | 21 ± 1        | Effective Stellar Temperature         |
| $r_*/r_{\text{in}}$ (10$^{-5}$) | 1.4 ± 0.2    | Stellar-to-inner radius ratio         |
| $A_V^{\text{CSE}}$ (mag)   | 2.0 ± 0.1     | Equatorial optical extinction         |

This variable is fixed in our model code and cannot be varied. The optical depth is an output of the ALS model.

Table 4. The Moffat filter profile parameters, $\alpha_{\text{mot}}$ and $\beta_{\text{mot}}$, for a bright field star at $J$ & $K$.

| Band | $\alpha_{\text{mot}}$ | $\beta_{\text{mot}}$ |
|------|------------------------|-----------------------|
| $J$  | 3.95 ± 0.06            | 2.4 ± 0.2             |
| $K$  | 3.03 ± 0.02            | 2.2 ± 0.3             |

polarized flux profiles to the data (Fig. 4 right). The best fit gives an equator-to-pole density contrast of 7.

Table 5. Photometric values for IRAS 19306+1407 collated from the literature: (1) Hrivnak et al. (2000), (2) Monet et al. (2003), (3) MSX Bands (Egan et al. 2003), and (4) Joint IRAS Science working group (1988).

| Band | Central wavelength (µm) | Flux density (10$^{-3}$ Jy) | Reference |
|------|-------------------------|-----------------------------|-----------|
| V    | 0.55                    | 7.40                        | (1)       |
| R    | 0.44                    | 2.21                        | (2)       |
| MSX A | 8.28                     | 1.16                        | (3)       |
| IRAS 12µm | 12.0                   | 3.58                        | (4)       |
| MSX C | 12.13                   | 3.65                        | (3)       |
| MSX D | 14.65                   | 9.12                        | (3)       |
| MSX E | 21.34                   | 46.27                       | (3)       |
| IRAS 25µm | 25.0                    | 58.65                       | (4)       |
| IRAS 60µm | 60.0                    | 31.83                       | (4)       |
| IRAS 100µm | 100.0                   | 10.03                       | (4)       |

Figure 5. High resolution images are available at [http://star-www.herts.ac.uk/~klowe/](http://star-www.herts.ac.uk/~klowe/). The observed SED and best model fits for IRAS 19306+1407. The dash line is the model fit and the solid black line is the model fit with interstellar reddening applied. References: (1) this paper, (2) Hrivnak et al. (2001), (3) Egan et al. (2003), (4) Monet et al. (2003), (5) Egan et al. (2003) and (6) Joint IRAS Science working group (1988).

3.2.2 DART model

The SED of IRAS 19306+1407 is plotted in Fig. 5 using published photometry and spectroscopy from a variety of sources, including this paper, and covering wavelengths from the $V$-band through to the sub-millimetre. The photometric values are listed in Table 5. The double-peaked nature of the SED is immediately evident, consisting of a redened stellar peak around 1.6 µm and a broad thermal dust peak between 30 and 40 µm due to the CSE. Double-peaked SEDs are typical of post-AGB stars with optically thin detached CSEs (van der Veen, Habing & Geballe 1989).

Our best-fitting model is shown in Fig. 5, both with and without correction for interstellar extinction (see below). Previous attempts to model the SED using amorphous carbon dust and a cooler F/G type star, were found not to provide sufficient flux in the dust peak (Hrivnak et al. 2001). We have treated the stellar temperature as a free parameter and determined a best-fitting value of 21,000 K, typical of a B1 type star. This is consistent within errors with the observationally determined spectral type of B0 (Volk et al. 2004; Kelly & Hrivnak 2003), where the colon denotes an uncertainty in the 0 (Hrivnak, private communication).

An optical extinction of $A_V = 2.0$ ± 0.1 mag, through the CSE in the equatorial direction, was determined from the model fit. We have investigated the effect of inclination of the nebula axis and have determined that the SED is consistent with a value of $0^\circ ± 5^\circ$. The extinction through the CSE along our line of sight is, therefore, also $A_V = 2.0$.

IRAS 19306+1407 lies close to the galactic plane, $l = 50.30^\circ$ and $b = -2.48^\circ$, and the SED will be affected by interstellar extinction. The extinction through the Galaxy...
Near-IR polarimetry and modelling of IRAS 19306+1407.

at this point is estimated to be \(A_V = 5.1 \pm 0.2\) mag. This value was obtained from the IRAS dust reddening and extinction service\(^6\), based on the data and technique in Schlegel, Finkbeiner & Davis (1998).

To correct the emergent model flux for interstellar extinction, we apply a reddening model developed by Cardelli, Clayton & Mathis (1989) which gives the extinction, \(A_\lambda\), at every wavelength between 0.1 and 3.3 \(\mu\)m for a given \(A_V\) and extinction ratio, \(R_V\). The extinction at shorter and longer wavelengths has been extrapolated. The DART model flux, \(F_{\text{DART}}\), is then modified to give the flux after correction for interstellar extinction, \(F_\lambda\):

\[
F_\lambda = F_{\text{DART}} \times 10^{-\frac{A_\lambda}{R_V}},
\]

Assuming a standard value of \(R_V=3.1\) for the ISM, then a fit to the SED shortward of 6 \(\mu\)m gives a value of 4.2 \pm 0.1 mag for interstellar extinction (solid curve in Fig. 3). The total extinction to the star is, therefore, 6.2 \pm 0.2 mag. This is consistent with the observed \(J-K\) colours. Assuming an extinction ratio \((R_V)\) of 3.1, and an intrinsic colour excess of \(E(J-K)_0 = -0.09\) for a B1 star, gives \(A_V = 6.4 \pm 0.7\) mag. The model parameters used in DART are presented in Table 3.

3.2.3 Distance estimate and derived parameters

The interstellar extinction can be used to estimate the distance of the post-AGB star. Using Yoshii (2003), based on extinction towards open clusters, gives an estimated extinction of 1.58\pm0.04 mag kpc\(^{-1}\). A visual extinction of 4.2 \pm 0.1 mag suggests a distance of 2.7 \pm 0.1 kpc, which we now adopt as our assumed distance from this point onwards.

Using this distance estimate gives values for \(r_{\text{in}}\) and \(r_{\text{out}}\) of 1.9 \pm 0.1 \times 10^{14} \text{m} and 2.7 \pm 0.1 \times 10^{15} \text{m} respectively. Multiplying \(r_{\text{in}}\) by \(r/r_{\text{in}}\) gives a stellar radius, \(R_\star\), of 3.8 \pm 0.6 R_\odot.

The stellar luminosity, \(L_\star\), is obtained by calculating the integrated flux under the model SED, giving values of 1800 \pm 140 and 4500 \pm 340 L_\odot, with and without interstellar reddening applied respectively, for the assumed distance. Post-AGB stellar evolution models suggest a lower limit of 2500 L_\odot for the central star of a PN (Schönenberger 1983), which means that IRAS 19306+1407 must be at least 2.0 kpc away to satisfy this criterion.

To calculate the time scales of mass loss, \(r_{\text{in}}\) and \(r_{\text{out}}\) are divided by the AGB wind speed. Only the H2 and Hα kinematic information are available for IRAS 19306+1407. These speeds arise from the shocks and fast winds in the post-AGB phase, and are not a true reflection of the AGB envelope expansion speed, therefore we have assumed a typical speed of 15 km s\(^{-1}\) from Neri et al. (1998). The age of the CSE is then 5700\pm160 yrs, became detached 400\pm10 yrs and the mass loss lasted 5300\pm160 yrs.

The number density of dust grains, \(N_0\), at \(r_{\text{in}}\) is calculated from the optical depth, the extinction cross section of the dust and the CSE thickness. The optical depth at 1.2 \(\mu\)m is 0.678 \pm 0.005, giving a value of \(N_0 = 6.1 \pm 3.0 \times 10^{11} \text{m}^{-2}\). Using \(N_0\) and integrating the dust density distribution gives the total dust mass (\(M_d\)), and assuming a dust grain bulk density of 3\times10^3 kg m\(^{-3}\), gives a value of 8.9 \pm 5.0\times10^{-4} M_\odot.

The gas-to-dust ratio for this object is unknown and we have adopted a value of 200 from Heras & Hond (2003). The total mass of the CSE is then 1.8 \pm 1.0 \times 10^{-4} M_\odot with an average mass-loss rate (\(\dot{M}\)) of 3.4 \pm 2.1\times10^{-5} M_\odot yr\(^{-1}\). The derived parameters given in this section are summarized in Table 3.

4 DISCUSSION

4.1 CSE geometry

The polarimetric observations, shown in Fig. 1, have been interpreted in terms of an axisymmetric shell with an equatorial density enhancement, which is optically thin in the near-infrared. The shell model successfully reproduces the observed SED from the V band to the sub-millimetre. As a further check on the validity of the model, the ALS code was run at the central wavelength of the F606W filter to simulate the HST observations shown in Fig. 2 (a). The results are shown in Fig. 6 and we find that the bipolar structure is reproduced, inclusive of the flattened contours in the centre of the HST image. A single axisymmetric shell model, based on the simple Kahn & West (1983) density distribution, can account for the morphology of this object over a wide range of wavelengths. The transition from bipolar nebula in the optical to limb-brightened shell in the near-IR is due to the variation in optical depth through the envelope with wavelength. At the wavelength of the HST observations, the CSE is optically thick along the equatorial direction and so light is preferentially funnelled along the polar axes before scattering into our line of sight, creating the bipolar lobes. The fact that the general appearance and extent of the lobes is reproduced by the model indicates that the density structure of the shell, in particular the equator-to-pole density contrast of 7, is reasonable. At near-infrared wavelengths, where the shell is optically thin along the equator, light is mainly scattered at the inner boundary in the equatorial plane, where the dust density is greatest, creating the shoulders seen in polarized flux in our observations.

Since our model calculations are limited to axisymmetric geometries, one aspect of the observations that we have not been able to account for is the non-orthogonality of the polarized flux shoulders, at PA 136 deg, and the major axis of the nebula, at PA 18 deg, illustrated in Fig. 2. A similar ‘twist’ has been detected in the mid-infrared images of IRAS 17456+5003, which has a curving polar axis (Gledhill & Yates 2003), and which was also modelled with an axisymmetric dust shell. A further similarity between the two objects is the unequal brightness of the polarized flux shoulders (see Gledhill et al. 2001). In the context of our model, these are due to scattering at the inner edge of the axisymmetric shell, so that the scattering optical depth is greater on one side of the shell than the other. Assuming that the dust properties are the same throughout the shell, then this suggests that there is a greater concentration of dust in the brighter shoulder. Further evidence for asymmetric dust distributions around post-AGB stars is seen in mid-infrared images of IRAS 07134+1005 (Daval et al 1998) and IRAS 21282+5050 (Meixner et al 1993, Gledhill & Yates 2003).

\(^6\) http://irsa.ipac.caltech.edu/applications/DUST
discuss possible causes for these asymmetries and conclude that they may arise due to interaction of the mass-losing star with a binary companion, although exactly how this happens is not clear. Volk et al (2004) imaged IRAS 19306+1407 using a narrowband H$_2$ filter (2.12 $\mu$m) and a narrowband K continuum filter (2.26 $\mu$m), to investigate the molecular hydrogen emission. Their continuum subtracted H$_2$uum filter (2.26 $\mu$m) seen in our polarized flux images. The ring can also be seen in their 2.26 $\mu$m continuum image, so that they have resolved the dust structure that we see in polarized flux. The similarity between the polarized flux and H$_2$ images suggests that the scattered light and molecular emission originate in the same region. Volk et al (2004) also detect faint extended H$_2$ emission lobes, extending from the ring, corresponding to the extended bipolar structure seen in the HST images (Fig. 2), oriented PA 18$^\circ$. It appears that the same axis twist seen in the scattered light images may be present in H$_2$ emission. Volk et al (2004) suggest that the H$_2$ ring seen in their images collimates the H$_2$-emitting bipolar lobes.

4.2 Estimation of the dust mass from our sub-mm observations

The mass of dust in the CSE, $M_d$, can be estimated from the IRAS 100 $\mu$m flux, $F_{100}$, and the SCUBA 850 $\mu$m flux. We have used the method stated in Gledhill, Bains & Yates (2002) to calculate an estimate of the dust mass from our observations. The dust temperature is estimated to be 146 ± 21 K, using Wien’s displacement law, with the peak dust emission at 35 ± 5 $\mu$m. The 850 $\mu$m flux value in Table I and $F_{100}$ = 10.03±1.30 Jy, gives an emissivity index of 1.3 ± 0.1. The assumed density for a silicate dust grain is $3 \times 10^3$ kg m$^{-3}$. The total dust mass in the CSE, using the assumed distance, is then 4.3 ± 0.7×10$^{-4}$ M$_\odot$, which is a factor of ~ 2 less than the value obtained from our radiative transfer model. The difference may arise from the simple assumptions inherent in the sub-millimetre estimate, particularly that of an isothermal CSE. The bulk of dust in the envelope will be cooler than 146 K (the minimum and maximum dust temperatures in the DART model are 130 and 40 K respectively), and will radiate on the long wavelength tail of the SED. An isothermal temperature of 100 K would result in a dust mass of 7.2 ± 1.7×10$^{-4}$ M$_\odot$. Given these approximations, we consider that the two results are comparable but that the more rigorous model calculations from DART and ALS provide a realistic value for the dust mass in the CSE.

4.3 CSE chemistry

We have modelled IRAS 19306+1407 using a silicate dust model, with grain sizes between 0.1 and 0.4 $\mu$m, which reproduces the shell-like morphology in the near-infrared, the observed degrees of polarization and the SED. However, we also find that a purely C-rich chemistry (amorphous carbon) using larger grains, typically >0.6 $\mu$m, can reproduce the observed polarization (Lowe & Gledhill 2003) and fit the overall shape of the SED, although this produces a poor fit at <1 $\mu$m after interstellar reddening is applied. Amorphous carbon also does not reproduce the shape of the SED between 10 and 20 $\mu$m. We have investigated the possibility that silicon carbide could fit the 10-20 $\mu$m region, but find that it provides too much flux at 11-12 $\mu$m and was in general a poor fit to the SED. These regions are modelled more effectively using Ossenkopf cold silicates.

As mentioned in Section 3.1, the simultaneous presence of emission from PAHs and crystalline silicates (Hrivnak et al 2003; Hodge et al 2004) suggests that the CSE has a mixed chemistry (both O- and C-rich). Our simple investigations of mixes of carbon and silicate dust in the CSE, show that amorphous carbon significantly dominates the SED at less than 1 per cent abundance. This suggests that If the 10-20 $\mu$m fits require silicate grains, then they must be the dominant dust component. However our models do not allow us to segregate the O- and C-rich material to have, for example, a region of silicate grains close to the star with a largely C-rich outflow at larger radii. Such a configuration has been proposed to explain observations of mixed chemistry objects (Molster et al 2002) in which the crystalline emission comes from cool silicates trapped in stable circumstellar or circumbinary discs. Matsuura et al (2004) have shown that in the mixed chemistry post-AGB object IRAS 16279-4757 the carbon-rich dust, traced by PAH emission, is located in a low-density outflow, while the continuum emission is concentrated toward the centre. Although our single component model, based on silicate grains, is reasonably successful in reproducing the observations, it is almost certain that the chemistry of IRAS 19307+1407 involves both O- and C-rich material, perhaps spatially segregated and with more than one size distribution.
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REFERENCES

Allamandola L. J., Tielens A. G. G. M., Barker J. R., 1989, ApJS, 71, 733
Arquilla R., Leahy D. A., Kwok S., 1986, MNRAS, 220, 125
Balick B., Frank A., 2002, ARA&A, 40, 439
Berry D. S., Gledhill T. M., 1999, Starlink User Note 223, available from http://star-www.rl.ac.uk
Cardelli J. A, Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Cohen M., Van Winkel H., Bond H. E., Gull T. R., 2004, AJ, 127, 2362
Dayal A., Hoffmann W. F., Beijing J. H., Hora J. L., Deutsch L. K., Fazio G. G., 1998 ApJ, 492, 603
Efstathiou A., Rowan-Robinson M., 1990, MNRAS, 245, 275
Egan M. P. et al., 2003, The Midcourse Space Experiment Point Source Catalog Version 2.3
Gledhill T. M., 2005, MNRAS, 356, 883
Gledhill T. M., Bains I., Yates J. A., 2002, MNRAS, 322, L55
Gledhill T. M., Chrysostomou A., Hough J. H., Yates J. A., 2001, MNRAS, 322, 321
Gledhill T. M., Yates J. A., 2003, MNRAS, 343, 880
Heras A. M., Hony S., 2005, A&A, 439, 171
Hodge T. M., Kraemer K. E., Price S. D., Walker H. J., 2004, ApJS, 151, 229
Hrivnak B. J., Volk K., Kwok S., 2000, ApJ, 535, 275
Joint IRAS Science working group, Infrared Astronomical Satellite Catalogs, 1988. The Point Source Catalog, version 2.0, NASA RP-1190
Joshi Y. C., 2005, MNRAS, 362, 1259.
Kahn F. D., West K. A., 1985, MNRAS, 212, 837.
Kelly D. M., Hrivnak B. J., 2005, ApJ, 629, 1040
Kwok S., 1993, ARA&A, 31, 63
Likkel L., 1989, ApJ, 344, 350
Likkel L., Forveille T., Omont A., Morris M., 1991, A&A, 246, 153
Lowe K. T. E., Gledhill T. M., 2005, in Adamson A., Aspin C., Davis C. J., Fujiyoshi T., eds, ASP Conf. Ser. Vol. 343, Astronomical Polarimetry: Current Status and Future Directions, Astron. Soc. Pac., San Fransico, p282

Table 6. The derived model parameters at the assumed distance of 2.7 kpc obtained from ALS† and DART‡ models.

| Parameter | Value | Units | Description |
|-----------|-------|-------|-------------|
| $R_*$     | 3.8 ± 0.6 | $R_\odot$ | Stellar Radius† |
| $r_{in}$  | 1.9 ± 0.1 | (10^{14}) m | Inner Radius‡ |
| $r_{sw}$  | 3.8 ± 1.0 | (10^{14}) m | Super-wind Radius‡ |
| $r_{out}$ | 2.7 ± 0.1 | (10^{15}) m | Outer Radius‡ |
| $L_*$     | 4500 ± 340 $L_\odot$ | Stellar Luminosity‡ |
| $N_0$     | 6.1 ± 3.0 | (10^{-3}) m^{-3} | Number density at $r_{in}$‡ |
| $M_d$     | 8.9 ± 5.0 | (10^{-4}) $M_\odot$ | Total mass of Dust‡ |
| $A_V$     | 4.2 ± 0.1 | mag | Interstellar extinction‡ |
| $T_{max}$ | 130 ± 30 | K | Temperature at $r_{in}$‡ |
| $T_{min}$ | 40 ± 20 | K | Temperature at $r_{out}$‡ |

*The apparent luminosity of the star, with applied interstellar reddening, is 1800 ± 140 L_\odot.
Matsuura M. et al., 2004, ApJ, 604, 791
Meixner M., Ueta T., Bobrowski M., Speck A., 2002, ApJ, 571, 936
Meixner M. et al., 1993, ApJ, 411, 266
Ménard F., 1989, PhD thesis, Univ. Montreal
Moffat A. P. J., 1969, A&A, 3, 455
Molster F. J., Waters L. B. F. M., Tielens A. G. G. M., Barlow M. J., 2002, A&A, 382, 184
Monet D. G. et al., 2003, AJ, 125, 984
Neri R., Kahane C., Lucas R., Bujarrabal V., Loup C., 1998, A&AS, 130, 1.
Omont A., Loup C., Forveille T., te Lintel Hekkert P., Habing H., Sivagnanam P., 1993, A&A, 267, 515
Ossenkopf V., Henning Th., Mathis J. S., 1992, A&A, 261, 567
Pégourié B., 1988, A&A, 194, 335
Preibisch Th., Ossenkopf V., Yorke H. W., Henning Th., 1993, A&A, 279, 577
Sahai R., Sánchez Contresas C. S., 2004, in Meixner M., Kastner J., Balick B., Soker N., eds, ASP Conf. Ser. 313, Asymmetric Planetary Nebulae III, Astron. Soc. Pac., San Francisco, p. 32
Sahai R. et al., 1998, ApJ, 493, 301
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Schönberner D., 1983, ApJ, 272, 708
Su K. Y. L., Hrivnak B. J., Kwok S, Sahai R., 2003, AJ, 126, 848
Ueta T., Murakawa K., Meixner M., 2005, AJ, 129, 1625
Ueta T., Meixner M., Moser D. E., Pyzowski L. A., Davis J. S., 2003, AJ, 125, 2227
Ueta T., Meixner M., Bobrowsky M., 2000, ApJ, 528, 861
van der Veen W. E. C. J., Habing H. J., Geballe, T. R., 1989, A&A, 226, 108
Van Winckel H., 2003, ARA&A, 41, 391
Volk K., Hrivnak B. J., Kowk S., 2004, ApJ, 616, 1181