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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 $\sim 3.4\times10^{-5}$ $M_{\odot}$ 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 proto-planetary 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 axisymmetric in some way (Gledhill et al. 2001; Gledhill 2005). Higher spatial resolution polarimetry using the Hubble Space Telescope (*HST*)

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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 2005; 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 H_2O masers (Likkel 1989) or CO emission (Arquilla et al. 1986; 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 that the object is a young PN. A further analysis of the *ISO* data by Hodge et al. (2004) confirms the presence of UIR features at 3.3, 6.2, and 7.7 µm, with the addition of the 8.6 and 11.2 µm features. These authors also mention the presence of silicate emission at 11, 19 and 23 µm, raising the possibility that *IRAS* 19306+1407 may have a mixed CSE chemistry.

Optical spectroscopy shows a broadened Hα emission line with line width of $\sim$2300 km s^{-1} indicating a fast outflow (Sahai & Sánchez Contreras 2004), as well as Hβ and [NII] emission, leading Kelly & Hrivnak (2005) to suggest a spectral type of approximately B0 for the star. A number of H_2 emission lines are seen in the *K*-band, with line ratios suggesting a mix of radiative and shock excitation (Kelly & Hrivnak 2005). Imaging through a narrow-band H_2 filter, centred on the 2.122 µm line, shows that the H_2 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.

2 OBSERVATIONS AND RESULTS

2.1 Imaging polarimetry observations and results

Polarimetric imaging at *J*- and *K*-band of *IRAS* 19306+1407 was obtained at the 3.8-m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawai'i, using the UKIRT 1-5 micron imager spectrometer (UIST) in conjunction with the infrared half-waveplate module (IRPOL2). A pixel scale of 0.12 arcsec was used and observations were made on 2003 June 8 with an average seeing of 0.5 arcsec. The total integration time for each filter was 237.6 seconds, comprising 24 exposures of 9.9 seconds each (see Table 1). Linear polarimetry was obtained by observing at four half-waveplate angles of 0°, 22.5°, 45° and 67.5°. The data reduction was carried out using STARLINK[1] 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 by 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 (1999).

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 (mJy)	Int. (s)	Size (arcsec × arcsec)
F606W[a]	13.81 ± 0.03	9.5 ± 0.3	300	3.2×2.0
F814W[b]	12.45 ± 0.02	26.1 ± 0.5	50	3.2×1.9
J[c]	11.18 ± 0.04	51.5 ± 0.8	237.6	3.9×2.4
K[d]	10.29 ± 0.12	48.4 ± 2.2	237.6	3.9×2.4
450W[e]	-	49.9 ± 38.7	1334[†]	-
850W[f]	-	14.1 ± 3.7	1334[†]	-

Notes: central wavelengths at [a]0.5888µm (Broad *V*), [b]0.8115µm (Johnson *I*), [c]1.25µm, [d]2.2µm, [e]450µm and [f]850µm; and [†]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 readout 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 they 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*-filters.

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 $I_{\rm J}$ 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 $I_{\rm K}$ image, but confusion due to the presence of the artefact stars makes this uncertain.

The polarized flux, produced by light scattering from

[1] Available from `www.starlink.ac.uk`

Figure 1. High resolution images are available at 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° 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° 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 (1985). 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-

Table 2. Summary of polarimetric results of *IRAS* 19306+1407 for each band, detailing the maximum polarization, integrated polarization and the position angle (E of N) of the major and minor axis of the nebula in polarized flux.

Band	Max. Pol. (per cent)	Integrated Pol.† (per cent)	PA_{major} (°)	PA_{minor} (°)
J	15 ± 6	1.7 ± 0.1	18	136
K	10 ± 4	1.3 ± 0.1	18	136

† - The integrated polarization over the source with apertures of radii of 1.7- and 1.4-arcsec for *J*- and *K*-band respectively.

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[2] 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 *F814W*- and *F606W*-filters with pivotal wavelengths of 5888 and 8115 Å respectively. The images were reduced using the On-the-Fly Reprocessing 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[3], and obtained magnitudes of 13.81 ± 0.03 and 12.45 ± 0.02 for *F606W* and *F814W* respectively (Table 1).

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.

Figure 2. High resolution images are available at http://star-www.herts.ac.uk/~klowe/. The *HST* ACS images, scaled logarithmically, of *IRAS* 19306+1407. (a) *F606W* (5888Å) scaled between 22 and 13 mag arcsec^{-2} with the angle of the major axis indicated by the arrow. (b) *F814W* (8115Å) scaled between 22 and 11 mag arcsec^{-2}. (c) *F606W* image, scaled as above, and *J*-band polarized flux contours. The lowest contour level is 19 mag arcsec^{-2} and subsequent contours are separated by 1 mag arcsec^{-2}.

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 Submillimetre 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 Submillimetre Observatory (CSO) tau relationship[4]. 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 $> 1\sigma$ and $> 3\sigma$ respectively inclusive of calibration errors. The fluxes obtained (Table 1) for F_{450} and F_{850} are 49.9 ± 38.7 mJy and 14.1 ± 3.7 mJy within a beam size of 7.5 and 14 arcsec respectively.

[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://www.stsci.edu/hst/acs/analysis/zeropoints

[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 (Efstathiou & Rowan-Robinson 1990) 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 (1985) 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 (1985) to model an axisymmetric shell, whilst recognising its limited ability to reproduce more complex morphologies:

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

where ρ_0 is the density at the pole ($\theta = 0^\circ$) at the inner radius, $r_{\rm in}$, and β specifies the radial density distribution. The azimuthal density distribution is determined by parameters ϵ and γ, which specify the equator-to-pole density ratio $(1 + \epsilon)$ and the degree of equatorial enhancement, respectively. An increase to γ flattens the density distribution, creating a more toroidal structure.

All parameters in Equation 1 are optimized in the model, apart from β, 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, $r_{\rm sw}$, modifying Equation 1 to:

$$\rho(r,\theta) = \rho_0 \left(\frac{r}{r_{\rm in}}\right)^{-\beta} \quad \text{when} \quad r > r_{\rm sw}. \qquad (2)$$

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

$$n(a) \propto a^{-q} \quad \text{for} \quad a_{\rm min} \leqslant a \leqslant a_{\rm max}. \qquad (3)$$

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), Pégourié (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 µm, with a variable grain size spacing typically 0.005 to 0.02 µm. 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° and 0.1×10^{-2} for the equator-to-pole contrast (ϵ), equatorial density enhancement (γ), inclination angle (θ) and the ratio of the inner-to-outer radii ($r_{\rm in}/r_{\rm out}$) respectively. The stellar temperature, T_*, was investigated using a series of Kurucz models [5] with solar metalicities 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 µm 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/. 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 $r \gtrsim r_{\rm in}$. To obtain a more realistic fit we use a Moffat filter profile:

$$M(r) \propto \left[1 + \left(\frac{r}{\alpha_{\rm mof}}\right)^2\right]^{-\beta_{\rm mof}}, \quad (4)$$

where r is radius from the source and $\alpha_{\rm mof}$ and $\beta_{\rm mof}$ 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-

Figure 4. High resolution images are available at 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, ϵ 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]	1.0 ± 0.01	Number fraction
$a_{\rm min}$ (μm)	0.10 ± 0.01	Minimum grain radius
$a_{\rm max}$ (μm)	0.40 ± 0.01	Maximum grain radius
q	3.5 ± 0.5	Grain size power law index
Common envelope model parameters		
$\beta^{\dagger}$	2	Radial density fall off
ϵ	6 ± 1	Equator-to-pole density contrast
γ	5 ± 2	Equatorial density enhancement
θ (deg)	0 ± 10	Inclination angle (from equator)
$r_{\rm in}/r_{\rm out}$ (10^{-2})	7 ± 1	Inner-to-outer radius ratio
ALS model parameters		
$\tau^{\ddagger}_{1.2}$ $(\times 10^{-1})$	6.78 ± 0.05	Optical depth at 1.2 μm
$\tau^{\ddagger}_{2.2}$ $(\times 10^{-1})$	1.13 ± 0.01	Optical depth at 2.2 μm
$r_{\rm sw}/r_{\rm in}$	2.0 ± 0.5	Super-wind to inner radius ratio
DART model parameters		
$T_{\star}$ $(10^3$ K)	21 ± 1	Effective Stellar Temperature
$r_{\star}/r_{\rm in}$ (10^{-5})	1.4 ± 0.2	Stellar-to-inner radius ratio
$A_V^{\rm CSE}$ (mag)	2.0 ± 0.1	Equatorial optical extinction

[1]Ossenkopf et al. (1992). †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, $\alpha_{\rm mof}$ and $\beta_{\rm mof}$, for a bright field star at J & K.

Band	$\alpha_{\rm mof}$	$\beta_{\rm mof}$
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 (Jy)	Reference
V	0.55	7.40×10^{-3}	(1)
R	0.44	2.21×10^{-2}	(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/. 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. (2000), (3) Ueta 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 reddened 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. 2000). 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 2005), where the colon denotes an uncertainty in the 0 (Hrivnak, private communication).

An optical extinction of $A_{\rm V} = 2.0 \pm 0.1$ 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 $0^{\circ} \pm 10^{\circ}$. The extinction through the CSE along our line of sight is, therefore, also $A_{\rm V} = 2.0$.

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 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_λ, at every wavelength between 0.1 and 3.3 µm for a given $A_{\rm V}$ and extinction ratio, $R_{\rm V}$. The extinction at shorter and longer wavelengths has been extrapolated. The DART model flux, $F_{\rm DART}$, is then modified to give the flux after correction for interstellar extinction, F_λ:

$$F_\lambda = F_{\rm DART} \times 10^{-\frac{A_\lambda}{2.5}}, \quad (5)$$

Assuming a standard value of R_V=3.1 for the ISM, then a fit to the SED shortward of 6 µm gives a value of 4.2 ± 0.1 mag for interstellar extinction (solid curve in Fig. 5). The total extinction to the star is, therefore, 6.2 ± 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 B1I star, gives $A_{\rm V} = 6.4 \pm 0.7$ 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 Joshi (2005), based on extinction towards open clusters, gives an estimated extinction of 1.58±0.04 mag kpc^{-1}. A visual extinction of 4.2 ± 0.1 mag suggests a distance of 2.7 ± 0.1 kpc, which we now adopt as our assumed distance from this point onwards.

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

The stellar luminosity, $L_\star$, is obtained by calculating the integrated flux under the model SED, giving values of 1800 ± 140 and 4500 ± 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 (Schönberner 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, $r_{\rm in}$ and $r_{\rm out}$ are divided by the AGB wind speed. Only the H_2 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±160 yrs, became detached 400±10 yrs and the mass loss lasted 5300 ± 160 yrs.

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

The gas-to-dust ratio for this object is unknown and we have adopted a value of 200 from Heras & Hony (2005). The total mass of the CSE is then $1.8 \pm 1.0{\times}10^{-1}$ M$_\odot$ with an average mass-loss rate ($\dot{M}$) of $3.4{\pm}2.1{\times}10^{-5}$ M$_\odot$ yr^{-1}. The derived parameters given in this section are summarized in Table 6.

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 (1985) 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 (Dayal 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 μm) and a narrowband *K* continuum filter (2.26 μm), to investigate the molecular hydrogen emission. Their continuum subtracted H_2 image (their Fig. 2 left) shows a broken ring with limb-brightened edges, which appears cospatial with the central dust structure, at PA 136, seen in our polarized flux images. The ring can also be seen in their 2.26 μm 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°. 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, $M_{\rm d}$, can be estimated from the *IRAS* 100 μm flux, F_{100}, and the SCUBA 850 μm 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 μm. The 850 μm flux value given in Table 1 and $F_{100} = 10.03 \pm 1.30$ 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 $4.3 \pm 0.7{\times}10^{-4}$ 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 maximum and minimum 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 $7.2 \pm 1.7{\times}10^{-4}$ 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 μm, 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 μm, can reproduce the observed polarization (Lowe & Gledhill 2005) and fit the overall shape of the SED, although this produces a poor fit at <1 μm after interstellar reddening is applied. Amorphous carbon also does not reproduce the shape of the SED between 10 and 20 μm. We have investigated the possibility that silicon carbide could fit the 10-20 μm region, but find that it provides too much flux at 11-12 μm 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. 2000; 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 μm 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.

Figure 6. High resolution images are available at http://star-www.herts.ac.uk/∼klowe/. A comparison of the *F606W HST* image and the raw model image from ALS at the central wavelength of the *F606W* filter. The model image has been rotated parallel to the long axis (PA = 18°) to match the *HST* image. The contours are spaced at an interval of 1 mag arcsec^{-2} from the peak value.

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

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

◇The apparent luminosity of the star, with applied interstellar reddening, is 1800 ± 140 $L_\odot$.

5 CONCLUSION

We present near-infrared polarimetric images of the dusty CSE of *IRAS* 19306+1407, in conjunction with new sub-millimetre photometry and archived *HST* images. The polarization vectors show a centrosymmetric structure with a maximum polarization of 15 ± 6 and 10 ± 4 per cent for *J*- and *K*-band respectively. The polarized flux shows a very faint elongated distribution at PA 18° with two bright scattering shoulders at PA 136°. The object is clearly bipolar in archived *HST* images, with the bipolar axis also at PA 18°

We model the polarimetric data using an axisymmetric light scattering code and a dust model based on sub-micron sized silicate grains. The observed polarization features are well described by a simple axisymmetric shell geometry, with an equator-to-pole density contrast of 7. The same shell model is used to fit the SED of *IRAS* 19306+1407 from optical to sub-millimetre wavelengths using an axisymmetric radiation transport code, to constrain the stellar temperature and radius, the optical depth of the CSE and the mass of dust in the CSE. We find that a B-type stellar spectrum, with T_*=21,000 K, best describes the SED, confirming previous suggestions that the object is an early PN.

The models give a value for the CSE and interstellar extinction of 2.0 ± 0.1 mag and 4.2 ± 0.1 mag respectively. We estimate a distance, from the interstellar extinction, of 2.7 ± 0.1 kpc and use this value to derive parameters from our models.

The polarimetric imaging shows deviations from axisymmetry that are beyond the scope of our model calculations. There appears to be a greater concentration of dust on one side of the star than the other, plus the axisymmetric shell is not aligned with the larger-scale bipolar axis, clearly seen in archive *HST* images. Similar features are seen in other post-AGB objects and may result from interaction of the mass-losing star with a binary companion. Further evidence for a binary nature is provided by the probable mixed chemistry nature of this object.

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