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Submillimetre photometry of post-asymptotic giant branch stars

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ABSTRACT

Stars in the post-asymptotic giant branch (post-AGB) phase of evolution are surrounded by detached circumstellar envelopes containing dust which emits thermally in the mid- and far-infrared. Here we present 850-μm SCUBA photometry of nine candidate post-AGB stars. All targets are detected at 850 μm and we use these fluxes to estimate the envelope dust masses and, by comparison with the 100-μm *IRAS* fluxes, the dust emissivity index.

Key words: stars: AGB and post-AGB – circumstellar matter – stars: mass-loss – submillimetre.

1 INTRODUCTION

The transition between the asymptotic giant branch (AGB) and post-AGB phases of stellar evolution is marked by a sharp decrease in mass-loss rate, as the central star evolves to hotter temperatures (e.g. Blöcker 1995). Post-AGB stars have typical spectral types of F and G and are surrounded by detached and slowly expanding ($\sim 15\,\mathrm{km\,s^{-1}}$) circumstellar envelopes (CSEs) of molecular gas and cool ($\sim 150\,\mathrm{K}$) dust. Thermal radiation from these dusty envelopes produces a mid- and far-infrared excess and the detached inner boundary results in a characteristic double-peaked infrared (IR) spectrum (van der Veen, Habing & Geballe 1989). Improvements in spatial resolution have allowed the detached CSEs of an increasing number of post-AGB sources to be directly imaged at mid-IR wavelengths (e.g. Dayal et al. 1998; Jura, Chen & Werner 2000; Ueta et al. 2001), permitting model fits to the envelope structure and to the spectral energy distribution (SED).

In this paper we present submillimetre photometry of nine candidate post-AGB stars with the following aims: (i) to provide submillimetre flux measurements to further constrain model fits to the far-IR SEDs, (ii) to estimate the dust emissivity index in the far-IR and (iii) to estimate the envelope dust masses. The targets have previously been observed using imaging polarimetry in the near-IR and are found to illuminate axisymmetric reflection nebulae (Gledhill et al. 2001). Both O- and C-rich stars are chosen as well as a range of near-IR envelope morphologies. In addition to objects that are fairly well defined as post-AGB (according to the definition of Kwok 1993), we include the mass-losing possible hypergiant star 19114+0002 (HD 179821) and two stars which may be still undergoing mass-loss (20056+1834 and 21027+5309).

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2 OBSERVATIONS AND DATA REDUCTION

Observations were made over eight nights between 1999 February 15 and May 26 using the SCUBA bolometer array (Holland et al. 1999) at the 15-m James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. SCUBA was operated in photometry mode to simultaneously obtain data at 850 and 450 μm through the 850N and 450N filters. The beamwidths are 13 and 7 arcsec, respectively, at 850 and 450 μm. Each 1-s exposure was repeated in a 3×3 jiggle pattern with 2-arcsec offsets to allow for slight pointing errors. After each jiggle pattern the telescope was chopped to sky using a chop throw of 120 arcsec. The data were reduced using the ORACDR pipeline software for SCUBA (Jenness & Economou 2000). Where possible, sky opacity correction was performed using the CSOFIT option, which corrects using a polynomial fit to the Caltech Submillimeter Observatory (CSO) tau data for each night and is considered to be more accurate than skydips. Where no fit was available, a standard skydip observation was used. Flux calibration was performed by observing either Mars, Uranus or CRL2688 to determine the antenna gain (flux conversion factor). On two nights (19990406 and 19990514) no suitable calibrator was observed and the default gains (240 and $800\,\mathrm{Jy\,V^{-1}}$ at 850 and 450 μm, respectively) were used. The measured gains were in the range 226 to $254\,\mathrm{Jy\,V^{-1}}$ at 850 μm and 626 to $872\,\mathrm{Jy\,V^{-1}}$ at 450 μm, which are typical of the ranges normally seen with SCUBA.

The results for 850 μm are shown in Table 1. For targets that were observed on more than one night the data have been combined. The flux errors are the errors on the mean flux over the number of exposures (each exposure is 1 s, so the number of exposures equals the integration time shown). This does not include calibration errors, for example those due to gain variation between observation of calibrator and target. SCUBA documentation states that the uncertainty in the gain is likely to be 7 per cent at 850 μm, although we found the gain to be stable to within 5 per cent.

3 RESULTS AND DISCUSSION

All targets are detected at 850 μm, with the possible exception of 18095+2704 where the signal is less than 2σ. In the case of 19500−1709, the observed coordinates were 10 arcsec east of the optical position of the star, so the flux here is a lower limit (as indicated in Table 1). It is possible that the 850-μm emission of our targets is extended relative to the SCUBA beam, in which case all fluxes are lower limits. However, a previous measurement of 19114+0002 at 800 μm by van der Veen et al. (1994) gave $F_{800} = 227 \pm 17$ mJy, which is identical within errors to our 850-μm measurement. These authors used the UKT14 instrument at JCMT, which had a clear aperture of 18 arcsec on the sky, larger than the 13-arcsec SCUBA beamwidth. As at optical and near-IR wavelengths 19114+0002 is the most extended envelope of our sample (Ueta, Meixner & Bobrowsky 2000; Gledhill et al. 2001), this then gives us confidence that, at 850 μm, our targets are not extended relative to the SCUBA beam.

At 450 μm we detected only two targets: $F_{450} = 166.7 \pm 43.9$ mJy for 17436+5003 and $F_{450} = 820.2 \pm 32.9$ for 19114+0002. However, as the SCUBA beamwidth is only 7 arcsec at 450 μm, it is unlikely that we are measuring all of the flux at this wavelength. A UKT14 (18-arcsec aperture) measurement of 19114+0002 gives $F_{450} = 1220 \pm 120$ mJy (van der Veen et al. 1994), substantially higher than our measurement. We therefore consider our 450-μm fluxes to be affected by the small SCUBA beamwidth and do not discuss them further.

Table 1. SCUBA photometry at 850 μm of post-AGB objects. The observation dates (Obs. Date) in 1999 are in day/month format, the total integration times (Int.) in s and the measured flux density (F_{850}) in mJy. Note that the flux errors do not include calibration errors and reflect the signal-to-noise ratio of the observations.

IRAS Target	Obs. Date	Int. (s)	F_{850} (mJy)
17436+5003	26/5	1350	47.8 ± 2.1
18095+2704	15/2, 16/2	1350	1.9 ± 1.5
19114+0002	17/2, 26/5	1062	233.5 ± 2.1
19475+3119	13/5	234	32.0 ± 5.4
19500−1709	17/2, 26/5	2250	>11.4 ± 1.4
20000+3239	6/4, 7/4	657	30.9 ± 2.5
20028+3910	7/4	450	35.5 ± 2.7
20056+1834	7/4, 14/5	1143	21.8 ± 1.8
21027+5309	14/5	448	15.0 ± 3.2

3.1 Dust emissivity

The dust emissivity at far-IR wavelengths is normally approximated by a power law, with emissivity $Q_\nu \propto \nu^p$, where p is the emissivity index. To estimate p for the objects in our sample we compare our measured 850-μm fluxes with the 100-μm *IRAS* fluxes and errors from the Point Source Catalog V2 (listed in Table 2). Assuming an optically thin dust shell, the flux from the shell at frequency ν is $F_\nu \propto Q_\nu B_\nu(T_\mathrm{d})$, where $B_\nu(T_\mathrm{d})$ is the Planck function for dust at temperature T_d. The expected flux ratio between frequencies ν_1 and ν_2 is then given by

$$F_{\nu_1}/F_{\nu_2} = (\nu_1/\nu_2)^p[B_{\nu_1}(T_\mathrm{d})/B_{\nu_2}(T_\mathrm{d})] \tag{1}$$

The values of p obtained for each target, assuming $T_\mathrm{d} = 120$ K, are given in Table 2.

Our choice of $T_\mathrm{d} = 120$ K will influence the estimated values of p, so we examine this assumption briefly. Model fits to the mid- and far-IR emission of detached dust shells indicate dust temperatures typically ranging from 140–200 K at the inner edge of the shell (e.g. Meixner et al. 1997; Dayal et al. 1998; Jura & Werner 1999). This is consistent with the observed type III and IV SEDs (van der Veen et al. 1989) which peak around 25 μm (Table 2). In practice, the dust will not be isothermal. For an optically thin shell in radiative equilibrium, the dust temperature decreases as $T_\mathrm{d}(\phi) \propto \phi^{-2/(4+p)}$, where ϕ is the angular offset from the star. For example, taking $T_\mathrm{d} = 170$ K at 1-arcsec offset from the star, then the dust temperature is 78 K at the edge of the 850 μm SCUBA beam for $p = 1$, so that emission from dust at a range of temperatures will be observed. However, a variation of ±30 K about $T_\mathrm{d} = 120$ K results in a variation in the estimated value of p of less than ∓ 0.1, which is within the errors for most of our sources. A further source of error in p could be overestimation of the 100 μm *IRAS* fluxes due to contamination by Galactic cirrus emission. We have examined the *IRAS* 100-μm images to determine the background level close to the sources. Apart from those with only an upper flux limit (L in Table 2), where background dominates the source fluxes as might be expected, the only other source where the background is comparable to the source flux is 19475+3119.

Table 2. Distance estimates, spectral types, O/C chemistry, SED classifications, near-IR morphology and 100-μm *IRAS* fluxes, from the literature. Where more than one distance estimate is found, the average is quoted. A dagger (†) indicates an assumed distance. The near-IR morphologies (from Gledhill et al. 2001) are S: Shell, B: Bipolar and C: Core-dominated. The derived values for the emissivity index, p, dust mass absorption coefficient, χ_{850} and envelope dust mass (powers of 10 in brackets) are given (see text).

IRAS Target	D (kpc)	Spec. Typ.	Chem.	SED	Morph.	F_{100} (Jy)	p	χ_{850} (cm^2 g^{-1})	M_d (M$_\odot$)
17436+5003	1.2[a]	F3Ib[b]	O[b]	IVa[e]	S	48.7 ± 3.4	1.5	1.6	4.5(−4)
18095+2704	2.2[f,e]	F3Ib[b]	O[b]	IVa[e]	B	5.6 ± 0.5	2.0	0.9	1.1(−4)
19114+0002	6.0[n]	G5Ia[c]	O[c]	IVb[e]	S	168.1 ± 20.2	1.4	1.8	5.0(−2)
19475+3119	5.4[n,v]	F3Ia[g]			S	14.8 ± 1.2	1.2	2.3	4.3(−3)
19500−1709	2.0[d,n]	F2-6[c]	C?[c,w]	IVb[e]	B	18.2 ± 2.0	<1.7	>1.2	>4.0(−4)
20000+3239	1.0†	G8Ia[b,h]	C[b,h]	III[q]	B	43.1L	<1.7	>1.2	<2.7(−4)
20028+3910	2.9[g,v]		C?[i]	III[p]	B	46.5 ± 4.7	1.7	1.2	2.7(−3)
20056+1834	0.5[m]	G0Ia[m]		600 K	C	2.8L	<0.6	>4.8	<1.2(−5)
21027+5309	1.8[l]	C8,3[l]	C[k,l]		C	8.0L	<1.2	>2.3	<2.2(−4)

Notes: [a]Skinner et al. 1994; [b]Meixner et al. 1999; [c]Hrivnak, Kwok & Volk 1989; [d]Bujarrabal, Alcolea & Planesas 1992; [e]van der Veen et al. 1989; [f]Hrivnak, Kwok & Volk 1988; [g]Likkel et al. 1991; [h]Hrivnak 1995; [i]Hu et al. 1994; [k]Kwok, Volk & Bidelman 1997; [l]Cohen & Hitchon 1996; [m]Menzies & Whitelock 1988; [n]Likkel et al. 1987; [p]Ueta et al. 2000; [q]Manchado et al. 1989; [v]Omont et al. 1993; [w]Justtanont et al. 1992.

3.1.1 *Variation across the sample*

For spherical grains composed of pure crystalline dielectric or metallic materials we expect $p = 2$, when the wavelength is much larger than the grain size (Bohren & Huffman 1983). A value of $p < 2$ may indicate an amorphous grain material, large grains ($x = 2\pi a/\lambda > 1$, where a is grain radius) and/or non-spherical grains. We know that most grains must be $< 1\ \mu$m in size ($x \ll 1$ in the far-IR) because near-IR polarimetric observations show that all the targets are significantly polarized, with many exhibiting linear polarizations of 20 per cent or more (Cohen & Schmidt 1982; Trammel, Dinerstein & Goodrich 1994; Gledhill et al. 2001). However, because different populations of grains may be responsible for the scattering and the far-IR emission, it is still possible that a value of $p < 2$ is due to the presence of large grains.

The first seven sources in Table 2 have F or G spectral types and/or type III or IV SEDs. Apart from 19475+3119, they have emissivity index in the range 1.4 to 2.0 (although two are upper limits). These objects are known to illuminate axisymmetric reflection nebulosities (e.g. Gledhill et al. 2001) and have been classified as post-AGB. The C-rich 21-μm feature source 20000+3239 (Kwok, Hrivnak & Geballe 1995) has $p < 1.7$, as has 19500−1709 which has a weak 21-μm feature (Justtanont et al. 1992). Although the chemistry of 20028+3910 is uncertain, it may be C-rich on the basis of a non-detection of OH (Hu et al. 1994) and has $p = 1.7$. The post-AGB nature of 19114+0002 is now doubtful (e.g. Jura, Velusamy & Werner 2001) but it is interesting that it has a similar emissivity index ($p = 1.4$) to 17436+5003 ($p = 1.5$). Both these sources are O-rich and possess optically thin, dusty CSEs with clearly resolved inner boundaries (e.g. Gledhill et al. 2001). They also have unusual spectral features in the 10–20 μm range (Justtanont et al. 1992) that may indicate a similar envelope chemistry. 19475 + 3119 is thought to be in the post-AGB phase (e.g. Kwok 1993) but has a near-IR scattering nebula with an unusual morphology. It also has unusual *IRAS* colours for a post-AGB star (the *IRAS* 60-μm flux is greater than that at 25 μm).

Both 21027+5309 and 20056+1834 are clearly different in nature to the other sources. They were found to have highly aligned polarization vectors in the near-IR (Gledhill et al. 2001) but with no evidence for a resolved scattering nebula, as seen in the other targets. This compact nature, in combination with evidence for ongoing mass-loss and variability, led these authors to suggest that both 21027+5309 and 20056+1834 are at an earlier phase of evolution and are still in the process of building up their CSEs. The high linear polarization of the carbon star 21027+5309 led Cohen & Schmidt (1982) to postulate an edge-on dust disc around this object. The SED of 20056+1834 peaks at $< 10\ \mu$m, indicating a warmer, ~600-K detached dust shell around this star (Menzies & Whitelock 1988). This object has an emissivity index of $p < 0.6$, much lower than the rest of the sample (note that increasing the value of $T_{\rm d}$ used to calculate p would reduce its value even further). Such a low value of p would normally indicate large grains, but its polarization in the J band is 14 per cent, and grains larger than a few microns would not produce this level of polarization by scattering. It is possible that the near-IR polarization in 20056+1834 is produced dichroically by extinction by aligned grains, which could also be large. This could explain the wavelength dependence of the polarization (14 per cent at J and 7 per cent at H; Gledhill et al. 2001) as well as the far-IR emissivity.

3.2 Dust masses

The 850-μm fluxes can be used to estimate the dust mass of the envelopes as they will be optically thin at this wavelength. Using the Rayleigh–Jeans form for the Planck function, the mass of radiating dust at temperature $T_{\rm d}$ responsible for the measured flux, F_ν, is given by (e.g. Hildebrand 1983)

$$M_{\rm d} = (F_\nu \lambda^2 D^2)/(2kT\chi_\nu), \tag{2}$$

where χ_ν is the dust mass absorption coefficient given for spherical grains of radius a and bulk density $\rho_{\rm gr}$ by

$$\chi_\nu = (3Q_\nu)/(4a\rho_{\rm gr}). \tag{3}$$

Approximating Q_ν as a power law such that

$$Q_\nu = Q_0 a(\lambda_0/\lambda)^p, \tag{4}$$

then with the assumption that $\lambda \gg a$, we may use the values $Q_0 = 40\ {\rm cm}^{-1}$ and $\lambda_0 = 250\ \mu$m given by Hildebrand (1983). With $\rho_{\rm gr} = 3\ {\rm g\ cm}^{-3}$ and using our calculated values for p we obtain dust mass absorption coefficients at 850 μm for each source (Table 2). Assuming $T_{\rm d} = 120$ K, equation (2) becomes

$$M_{\rm d}({\rm M}_\odot) = 1.06\times10^{-5} F_{850}({\rm mJy}) D^2({\rm kpc})/\chi_{850}({\rm cm}^2\ {\rm g}^{-1}), \tag{5}$$

giving the estimated dust masses shown in Table 2. These estimates of $M_{\rm d}$ are likely to be uncertain by at least a factor of 2, reflecting the uncertainty in the distance estimate and our assumption that $T_{\rm d} = 120$ K. Where dust masses have previously been estimated, our results are generally consistent within errors for an equivalent distance. In the case of 19114+0002, the SCUBA estimate of 0.05 $\rm M_\odot$ is consistent with previous estimates of 0.03 and 0.04 $\rm M_\odot$ from mid-IR imaging (Jura & Werner 1999; Hawkins et al. 1995) and 0.08 $\rm M_\odot$ from near-IR scattering models (Gledhill & Takami 2001). Likkel et al. (1991) estimate dust masses for six of our targets from 60-μm *IRAS* fluxes and, for an equivalent distance, these agree within a factor of 2 with our results, with the exception of 20000+3239, where our estimate is 10 times greater.

The derived dust masses may be used to estimate the mass of gas in the envelope by assuming a value for the gas-to-dust mass ratio. Assuming a gas-to-dust mass ratio of 200 then, with the exception of the probable hypergiant 19114+0002, the post-AGB candidates have CSE masses of less than 1 $\rm M_\odot$ using the distances given in Table 2. Of these, only 19475+3119 and 20028+3910 have masses greater than 0.1 $\rm M_\odot$. The smallest CSE mass is measured for 20056+1834, which again may indicate its relative youth. Independent estimates of the CSE mass may be obtained from CO measurements: Bujarrabal et al. (2001) quote CO masses of 6.1×10^{-2} and 5.5 $\rm M_\odot$, respectively, for 17436+5003 and 19114+0002 (adjusted for differences in assumed distance), both of which would be consistent within a factor of 2 with our estimates assuming a gas-to-dust mass ratio of 200.

4 CONCLUSIONS

We present 850-μm SCUBA photometry observations of nine candidate post-AGB stars, all of which are detected, indicating that they possess dusty circumstellar envelopes (CSEs). We calculate p, the exponent of the dust emissivity ($Q_\nu \propto \nu^p$), from the 100- and 850-μm flux ratios and find that p lies in the range from 1.4 to 2 for objects that are thought to be sources with detached envelopes (six out of nine sources). The remaining three objects are disparate from the detached envelope sources in a number of ways and have lower values of p. This is especially true of 20056+1834, where $p < 0.6$ may indicate large grains, in which case the observed near-IR polarization of this object could be due to dichroic extinction. We use the 850-μm fluxes to estimate the dust masses of the CSEs and find that they are in general agreement with previous estimates. Assuming a gas-to-dust mass ratio of 200 then, with the exception of the probable hypergiant star 19114+002, we find that only two sources, 19475+3119 and 20028+3910, have CSE masses greater than 0.1 $M_\odot$. However, uncertainties in the distances to these sources precludes too much interpretation; if the distances are underestimated then the envelope masses will be correspondingly ($\propto D^2$) greater.

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