BIG, BUMPY DUST SHELLS AROUND PROTOPLANETARY NEBULAE

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Abstract We present evidence for parsec-sized dust shells around post-AGB objects, seen in ISOPHOT data. Furthermore, some of these data show evidence for enhanced mass-loss episodes on the timescales of thermal pulses. Preliminary studies suggest that the mass of the progenitors of these stars should be of the order of $\sim 3M_{\odot}$.

1. INTRODUCTION

In order to fully understand protoplanetary nebulae (PPNe) we need to study the stars from which they evolve. The direct precursors of the PPN are believed to be the asymptotic giant branch (AGB) stars, which suffer intensive mass-loss and become surrounded by circumstellar dust shells. These circumstellar shells form the nebulae seen as PPN. However, the mass-loss processes are not well understood. Several models exist which suggest that the mass-loss could be constant, varying, episodic or steadily increasing (e.g. van der Veen & Habing 1988; Vassiliadis & Wood 1993, hereafter VW), but there is little observational data to clarify the situation. The most promising theoretical models suggest that mass-loss is due to a combination of stellar pulsation and radiation pressure on dust grains (e.g Höfner & Dorfi 1997)

While there is evidence that the mass-loss from these objects becomes asymmetric towards the end of the AGB (e.g. Josselin et al. this volume; Ueta et al. 2000), studies of the dust (e.g. Mauron & Huggins 1999) and gas (Olofsson et al. 2000) around AGB stars shows that they initially have fairly symmetric mass-loss. Furthermore, the velocity of the outflowing material seems to be fairly constant (e.g. Huggins et al. 1988).

Therefore, the PPN dust shells contain a fossil record of the mass-loss from the precursor AGB stars. We present an ISOPHOT far-infrared imaging study of three PPNe: oxygen-rich HD 161796, and carbon-rich AFGL 2688 and AFGL 618.

2. OBSERVATIONS

We have obtained linear scans of the thermal emission from three PPN using the ISOPHOT AOT PHT32. Details of the observations are listed in Table 1. A more detailed discussion of the the observations, as well as the data reduction techniques, can be found in Speck et al. (2000a; 2000b).

Table 1 Observations

Source	filter (μm)	scan length	image pixel size	θ^*	spectral type	CS† chem.
AFGL 618	120/180	$53'$	$30''\times92''$	9°	B0	C
AFGL 2688	120/180	$53'$	$30''\times92''$	8°	F5I	C
HD 161796	90/160	$36'/53'$	$15''\times46''/30''\times92''$	28°	F2-F5	O

* θ is the orientation of the scan, measured east of north.
† Chemistry of the circumstellar envelope.

3. RESULTS

HD 161796 is a low metallicity supergiant which is believed to have recently left the AGB on its way to becoming a planetary nebula (PN; Hrivnak et al. 1989). At first glance this object looks like a point source (Fig.1̃a). However, if we look at the $\sim$1-2% flux level (Fig.1̃b) we can see that the observation deviates from a point source to show weak extended emission out to a radius of $\sim400''$. We have simulated the extended emission using a mapping simulator (Gabriel & Hur 2000) in

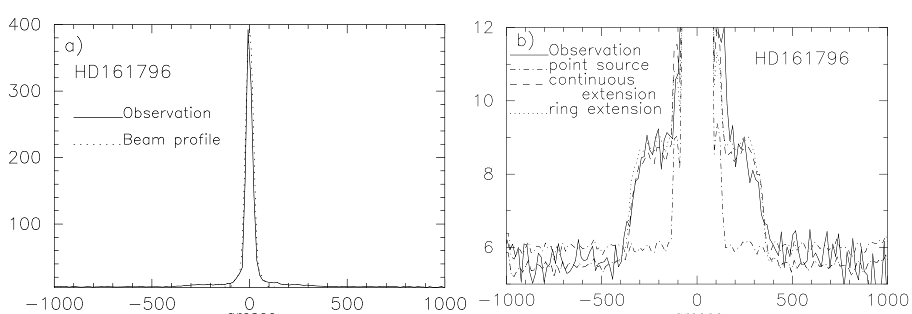

Figure 1 HD 161796 at 90μm: a) scan profile together with the beam profile; b) close up on the extended emission: scan profile together with the a simulated point source and two simulated extended sources. y-axes = brightness in MJy/sr.

the ISOPHOT interactive analysis (PIA) package (Gabriel et al. 1997)[1]. The simulations shown in Fig.$\tilde{1}$b demonstrate that our 1-D scans have insufficient resolution to distinguish between a point source with a continuous extended source and a point source surrounded by a detached ring with an inner radius of up to 50″. Therefore, for this object, we cannot determine whether mass-loss has been continuous or episodic.

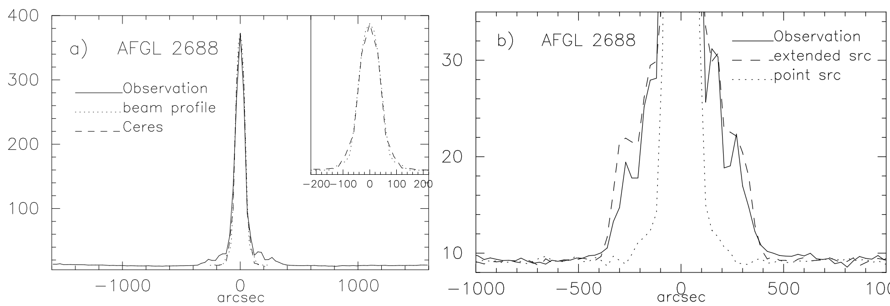

Figure 2 AFGL 2688 at 120μm: a) scan profile (solid line) together with the beam profile (dotted line) and the scan profile of Ceres (dashed line), a point source with similar peak flux to AFGL 2688 at 120μm and observed using the same AOT; b) close up on the extended emission: scan profile together with the simulated point and extended sources. y-axes = brightness in MJy/sr.

Like HD 161796, AFGL 2688 is believed to have left the AGB in the last few hundred years (e.g. Skinner et al. 1997). In Fig.$\tilde{2}$a the 120μm scan of AFGL 2688 shows a bright point source surrounded by less bright (∼10%) extended emission out to ∼350″. Fig.$\tilde{2}$a shows that the distribution of the extended emission is not smooth, but rather shows enhancements at certain radii from the central point source. This is demonstrated more clearly in Fig.$\tilde{2}$b, an enlargement at the 10% flux level which also shows the simulated emission using the PIA map simulator. Enhanced emission occurs at radii of about 150″ and 300″.

AFGL 618 is considered to be either an evolved PPN or a very young PN. This object has progressed further along the path from the tip of the AGB to the PN phase than the previous two objects. Fig.$\tilde{3}$(a&b) shows that the thermal emission from AFGL 618 closely resembles that of AFGL 2688, showing a bright point source surrounded by lower level (∼10% flux) "bumpy" extended emission out to ∼400″. The enhanced emission bumps occur at radii of 160″ and 275″ in the simulated extended emission. Fig.$\tilde{4}$ shows that the emission bumps appear at slightly different radii for the two C-rich objects. Moreover, these emission bumps

[1]This simulator allows us to "build" an object out point sources and continuous extended sources, convolve it with a beam profiles and produce an image of how this object would appear if observed using PHT32. See Gabriel & Hur (2000) for details

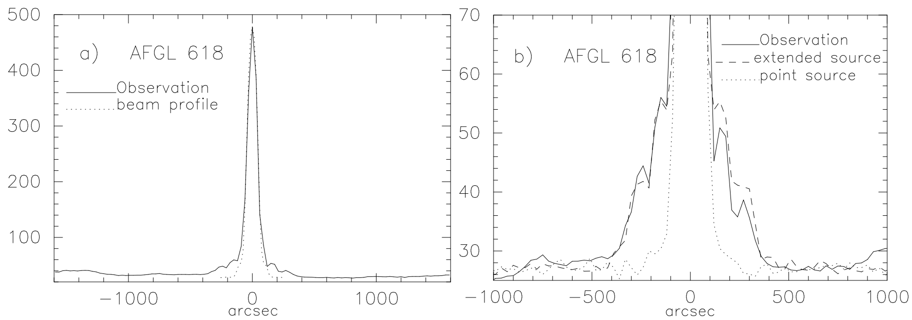

Figure 3 AFGL 618 at 120μm: a) scan profile (solid line) together with the beam profile (dotted line); b) close up on the extended emission: scan profile together with the simulated point and extended sources. y-axes = brightness in MJy/sr.

occur at the same position when the same object is observed at different wavelengths (120 and 180μm), indicating that they are not related to instrumental effects.

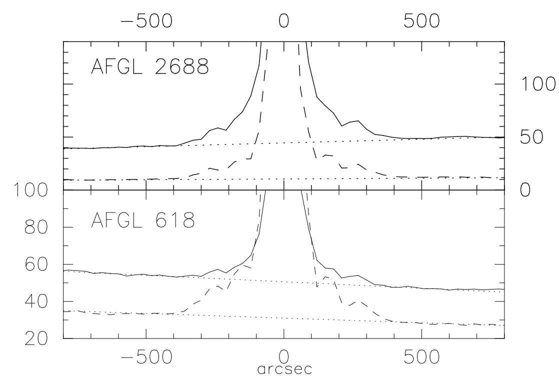

Figure 4 Comparison of the scans for AFGL 2688 and AFGL 618. solid lines = 120μm profiles; dashed lines = 180μm profiles; dotted lines = background level

4. DISCUSSION

Using our observations together with expansion velocities and distances from the literature, we can deduce the timescales associated with mass-loss for these objects. These are shown in Table 2. If we assume that we are observing the entire dust shell, then $t_{\rm AGB}$ represents the time these stars were in the mass-losing AGB phase. Furthermore, the enhanced emission seen in the observations of the two C-rich objects (AFGL 2688 and AFGL 618) is assumed to be due to enhanced mass-loss caused by thermal pulses (e.g VW; Steffen et al. 1998), which implies that the time between the ejection of the enhancements gives the time between thermal pulses ($t_{\rm interpulse}$). We can compare these

Table 2 Radii and timescales dervied from the observations

Source	Distance (kpc)	v_{exp} (km/s)	R_{max} (pc)	t_{AGB} (10^4yrs)	R_1 (pc)	t_1 (10^4yrs)	R_2 (pc)	t_2 (10^4yr)
AFGL 618	1.8	~20	~3.5	~17	~1.3	~6.4	~2.6	12.8
AFGL 2688	1.2	22.4	~2.0	~9	~0.87	~3.7	~1.7	7.4
HD 161796	1.2	12	~2.3	~19	...	...	...	...

v_{exp} = the expansion velocity from CO rotation lines; t_{AGB} = time since oldest part of dust shell was ejected*; R_1 = radius of inner emission enhancement; R_2 = radius of outer emission enhancement; t_1 = time since inner enhancement was ejected*; t_2 = time since outer enhancement was ejected*; * all ages assume constant expansion velocity;

timescales with those computed through the stellar evolution models of VW. Table 3 lists $t_{interpulse}$, t_{AGB} and the average duration of pulses, t_{Swind}, for various progenitor masses, together with the timescales for AFGL 2688 and AFGL 618. The resolution of our scans only constrains the upper limit of t_{Swind} for these objects.

Table 3 Timescales for thermal pulses/enhanced mass-loss from VW

M_{MS} ($M_\odot$)	$t_{interpulse}$ (10^5yrs)	t_{AGB} (10^5yrs)	t_{Swind} (10^3yrs)
0.945	~1	5.704	0.4
1	~1	6.502	0.8
1.5	~1	9.385	0.8
2	~0.9	13.39	6
2.5	~0.7	18.27	4
AFGL 618	*~0.53*	*1.6*	*<10*
AFGL 2688	*~0.37*	*0.9*	*<10*
3.5	~0.3	3.509	9
5	~0.1	3.601	3

M_{MS} is the main sequence mass. Z=0.008

The outflows of both AFGL 2688 and AFGL 618 have been modeled to derive mass-loss rates based on CO observations (e.g Skinner et al. 1997; Meixner et al. 1998). These modeled mass-loss rates are of the order of a few $\times 10^{-5} M_\odot yr^{-1}$. Taking the duration of this mass-loss to be t_{AGB}, we find the total mass lost by the star to be approximately $3M_\odot$. If the remnant star has a mass in the range 0.6-1$M_\odot$, that gives a total mass for the progenitors of these objects of $<4M_\odot$, in reasonable agreement with the value of $\sim 3M_\odot$ from Table 3. Estimates of the mass-loss rate for HD 161796 suggest a value of $<10^{-5} M_\odot yr^{-1}$ (see Likkel et al. 1987). Using t_{AGB} from Table 2 gives a mass for the entire dust shell of $<2M_\odot$. Again, we assume that the mass of the remnant star is in the range 0.6-1$M_\odot$, giving a mass for the progenitor of $\lesssim$2.5-3$M_\odot$, slightly smaller than for the C-rich objects.

5. CONCLUSIONS

There is evidence for extremely extended dust emission (radius$\gtrsim$1pc) around the three PPNe presented here. The sizes of these dust shells can be used to calculate their ages ($1-2\times10^5$yrs). For the C-rich objects there also appear to be periodic enhancements on a timescale of a few $\times10^4$yrs, which may coincide with thermal pulses on the AGB. Comparison with models suggest that the C-rich stars evolved from progenitors with masses of $\sim$3-4$M_\odot$, while the O-rich object seems to have evolved from a slightly less massive progenitor, $\lesssim$2.5-3$M_\odot$.

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