A SPITZER STUDY OF THE MASS-LOSS HISTORIES OF THREE BIPOLAR PREPLANETARY NEBULAE

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ABSTRACT

We present the results of far-infrared imaging of extended regions around three bipolar preplanetary nebulae, AFGL 2688, OH 231.8+4.2, and IRAS 16342−3814, at 70 and 160 µm with the MIPS instrument on the Spitzer Space Telescope. After a careful subtraction of the point-spread function of the central star from these images, we place constraints on the existence of extended shells and thus on the mass outflow rates as a function of radial distance from these stars. We find no apparent extended emission in AFGL 2688 and OH 231.8+4.2 beyond 100" from the central source. In the case of AFGL 2688, this result is inconsistent with a previous report of two extended dust shells made on the basis of ISO observations. We derive upper limits of $2.1 \times 10^{-7}$ and $1.0 \times 10^{-7} M_\odot$ yr$^{-1}$ for the dust mass-loss rates of AFGL 2688 and OH 231.8, respectively, at 200" from each source. In contrast to these two sources, IRAS 16342−3814 does show extended emission at both wavelengths, which can be interpreted as a very large dust shell with a radius of ~400", a thickness of ~100", corresponding to 4 and 1 pc, respectively, at a distance of 2 kpc. However, this enhanced emission may also be Galactic cirrus; better azimuthal coverage is necessary for confirmation of a shell. If the extended emission is a shell, it can be modeled, with some assumptions about its dust properties, as enhanced mass outflow at a dust mass outflow rate of $1.5 \times 10^{-7} M_\odot$ yr$^{-1}$ superimposed on a steady outflow with a dust mass outflow rate of $1.5 \times 10^{-7} M_\odot$ yr$^{-1}$. Because of the size of the possible shell, it is likely that this shell has swept up a substantial mass of interstellar gas during its expansion, so these estimates are upper limits to the stellar mass-loss rate. We find a constant color temperature of 32 K throughout the circumstellar envelope of IRAS 16342−3814, which is consistent with heating by the interstellar radiation field.

Key words: planetary nebulae: individual (AFGL 2688, OH 231.8+4.2, IRAS 16342−3814) — stars: AGB and post-AGB — stars: mass loss

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1. INTRODUCTION

Preplanetary nebulae (PPNe) represent a fleeting stage of stellar evolution. These transitional objects arise between the rapid mass-loss phase at the end of the asymptotic giant branch (AGB) and the ionized planetary nebula stage. AGB stars are important because they are the Galaxy’s main mechanism for the replenishment of dust and gas into the interstellar medium (ISM), ejecting most of their mass in a few $10^5$ yr because of their high mass-loss rates. By looking at the circumstellar material around PPNe, we can see an imprint of the activity of the earlier AGB. PPNe are also in a stage where the geometry of the mass loss from the central star usually changes from spherically symmetric to an axially symmetric bipolar outflow, as illustrated in the HST images of AFGL 2688 (Sahai et al. 1998). In these images, a spectacular bipolar structure is superimposed on a set of concentric shells of gas and dust ejected near the end of the AGB. In the study reported here, we have attempted to characterize the mass-loss behavior of the progenitor AGB stages of three systems that are now bipolar.

Using the direct detection of infrared emission from dust lost over as much as $10^5$ yr during the AGB, it is possible to study the mass-loss histories of these objects. There has been a dearth of observations of large extended shells of evolved stars out to the distances sampled in this project primarily because of the difficulty in observing in the far-infrared, where the cool dust has its peak emission. With the Spitzer Space Telescope (Werner et al. 2004), the far-infrared is now accessible at a resolution and sensitivity sufficient to potentially resolve the structures of these dust shells, and thereby to test theories of mass loss in AGB stars.

Several tantalizing cases were observed by IRAS, showing that large dust shells exist around some evolved stars. For example, Gillett et al. (1986) found that R CrB shows a very large shell with a radius of 4 pc, and Hawkins (1990) reported a dust shell with a diameter of 30′−40′ (~1 pc) around W Hya. However, these observations could not resolve the structure that may be present in the shells or address the possibility of multiple shells. If the mass-loss rate during the AGB is constant, we should expect to see a smooth envelope with column density declining as 1/b, where b is the displacement from the star in the sky. However, if the mass-loss rate fluctuates as the star goes through thermal pulses during the AGB, as the models suggest (e.g., Vassiliadis & Wood 1993), then we should see enhanced emission in the form of multiple dust shells around our objects. For example, Speck et al. (2000) reported on the basis of Infrared Space Observatory (ISO) data that there are large concentric shells in AFGL 2688 and AFGL 618. This result is among a small set of observations showing evidence for periodic mass loss caused by thermal pulsation, as well as the timescale between thermal pulses predicted by AGB evolutionary models (e.g., Vassiliadis & Wood 1993). Confirmation of these shells at higher resolution and greater sensitivities motivated our selection of AFGL 2688 as a target for this study. There have been no previous claims of large-scale dust emission from OH 231.8+4.2 (hereafter OH 231.8) or IRAS 16342−3814. However, they are currently very young PPNe with high mass-loss rates of
approximately $10^{-4} M_\odot$ yr$^{-1}$ (Alcolea et al. 2001; Sahai et al. 1999), which suggests that the emission from dust produced during the AGB may be readily visible.

Here we report on the lack of very extended emission, spherically symmetric or otherwise, from AFGL 2688 and OH 231.8. However, we do see possible evidence for a very large diffuse dust shell around IRAS 16342–3814 with a radius of 400", although this extended emission might also be from Galactic cirrus.

2. OBSERVATIONS AND DATA REDUCTION

AFGL 2688 (the Egg Nebula), OH 231.8, and IRAS 16342–3814 were observed with the MIPS instrument (Rieke et al. 2004) at 70 and 160 \(\mu m\) on Spitzer. These PPNe were observed along two mutually perpendicular scan paths in order to sample dust emission out to about 800" from the central source and to determine background levels. At 70 \(\mu m\) the scan paths are 15' $\times$ 3.0' in one direction and 11' $\times$ 7.7' in the other, while at 160 \(\mu m\) the scan paths are 15' $\times$ 2.6' and 10.5' $\times$ 6.5'. The pixel scale is 9.2'' at 70 \(\mu m\) and 16'' at 160 \(\mu m\). However, the central sources were not directly observed in order to avoid persistence artifacts from these bright sources. This observing strategy limits the azimuthal coverage of the sources but should give an adequate estimate of the presence of well-defined shells or asymmetries such as large-scale bipolarity.

The basic science calibrated data (BCD) were reduced using the software package MOPEX$^1$ from the Spitzer Science Center (SSC). MOPEX was used for rejecting outliers, as well as for co-adding and mosaicing the individual BCD frames to create the final image. Further reduction was done manually to remove striping due to bright latents as described in the MIPS data handbook.$^2$ The correction involved finding the median value measured for every pixel from a series of BCD frames far from the central source, where we assume that there is no extended emission, then subtracting this median from each data frame before co-adding and mosaicking. The median subtraction removes both the bright latents and the uniform component of background emission. Figure 1 shows the final mosaicked images.

The most prominent features of the 70 \(\mu m\) images of the bipolar targets are the diffraction spikes from the point-spread function (PSF) of the central source. Although we did not image the central star, the wings of the PSF are still present and bright out to about 200'' from the source. At 160 \(\mu m\), the PSF is less pronounced, but we see much more background than at 70 \(\mu m\) from Galactic cirrus. The Galactic cirrus emission presents a problem in determining the true sky background, since it covers much of our fields. For both the 70 and 160 \(\mu m\) images, we use the median surface brightness of regions of low and uniform brightness far from the central source as an estimate of the sky background. This procedure removes a uniform background from the images, retaining possible enhanced emission from the source and Galactic cirrus. The uncertainty in the background (see below) at 160 \(\mu m\) is higher than at 70 \(\mu m\) because it is more difficult to find a large patch of uniform surface brightness to estimate the sky background.

2.1. Sensitivities

The sensitivity of our data is estimated by examining the standard deviation of a patch of uniform background far from the source both before and after the median background subtraction method described above. For AFGL 2688, before background subtraction, the mean of a patch in the eastern scan path at 70 \(\mu m\) is 14.1 MJy sr$^{-1}$ with a standard deviation of 1.11 MJy sr$^{-1}$. Some of the variance in the background is likely from the effects of bright latents from the detector pixels, which are removed by the median background subtraction described above. After median subtraction, the mean background is at 0.6 MJy sr$^{-1}$ with a standard deviation of 0.92 MJy sr$^{-1}$. The mean surface brightness at 160 \(\mu m\) before background subtraction is 31.45 MJy sr$^{-1}$ with a standard deviation of 1.67 MJy sr$^{-1}$. After background subtraction, the mean is at 0.33 MJy sr$^{-1}$ with a standard deviation of 1.51 MJy sr$^{-1}$. The sensitivity for OH 231.8 is better than for AFGL 2688, probably because of the lower sky background levels. The sensitivity for IRAS 16342–3814 is comparable to that of AFGL 2688 at 70 \(\mu m\) but worse at 160 \(\mu m\) due to a higher sky background and greater presence of Galactic cirrus. The mean background and sensitivities for all three sources at 70 and 160 \(\mu m\) are given in Tables 1 and 2, respectively.

2.2. PSF Subtraction

Since the PSF pattern from the central source is so prominent at 70 \(\mu m\), we attempted to fit a model PSF to our images in order to subtract the bright central source in search of extended dust emission near the source. The stinytim software provided by the SSC was used to generate model PSFs. We chose to use the default MIPS throughput curve along with a blackbody spectrum at several temperatures ranging from 20 to 100 K. See Figure 2 for examples of the model PSFs. Multidimensional fitting was carried out for our images in order to minimize the residuals of the PSF subtraction using various \(x-y\) shifts, as well as the scaling of the PSF flux values. The best fit was found by minimizing the square root of the sum of the squares of the differences in flux. We found several limitations in the model PSFs when attempting to subtract the PSF from the images. Even for the best-fit PSFs, the subtraction still leaves some obvious PSF residuals at a level of $10^{-4}$ relative to the peak as extrapolated from the model PSF. These residuals show that the wings of the model PSF are not well characterized at that flux level. The PSF subtraction also tends to leave portions of the region within the Airy ring with negative flux values. The most likely reason is a nonlinear pixel response as the pixels approach saturation, so that although the model has a higher brightness value closer to the core of the PSF, the actual pixel values are leveling off for our bright sources. Unfortunately, there are currently no empirical data on the MIPS 70 or 160 \(\mu m\) PSF to compare to the model PSF at distances greater than 100'' from the peak. Beyond about 240'', PSF features are no longer present in the MIPS images, so our ability to detect extended emission there is only limited by background and integration time.

The results of PSF subtraction for AFGL 2688 are shown in Figure 3. Note the remaining features near the north and at a position angle of $\sim$50' east of north, about 150'' from the location of the source in the PSF subtraction in Figure 3a. This residual can also be seen in roughly the same region of the 70 \(\mu m\) PSF subtraction of OH 231.8 in Figure 4. It seems unlikely that these features are physical, but the northern feature in AFGL 2688 does align with its bipolar outflows, seen in the optical and infrared but observed within the inner 10'' of the PPN. The blob in AFGL 2688 at a position angle of $\sim$50' also roughly aligns with the outflow direction seen in previous CO observations (Skinner et al. 1997), also at around 10'' from the central star. The fact that the features we see are nearly 200'' from the source and lie almost on top of the diffraction rays of the original PSF casts doubt on their reality. This dilemma cannot be resolved until a well-sampled empirical PSF out to several arcminutes is available. We may be seeing possible features in the wings of the actual PSF that the model has failed to reproduce.

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1. Available at http://ssc.spitzer.caltech.edu/postbed/.
2. Available at http://ssc.spitzer.caltech.edu/mips/dh/.
Fig. 1.—Our three PPNe after mosaicking and background subtraction. The units of the color bars are MJy sr$^{-1}$. The bars in the images are 200$''$ in length for scale, and the cross marks the location of the point source. *Top:* AFGL 2688. *Middle:* OH 231.8. *Bottom:* IRAS 16342–3814. Note the prominence of the PSF features at 70\,$\mu$m in all the images. At 160\,$\mu$m, the PSF is not apparent in IRAS 16342–3814. North is up, and east is to the left.

### TABLE 1

| Object                  | Mean before Subtraction (MJy sr$^{-1}$) | $\sigma$ (MJy sr$^{-1}$) | Mean after Subtraction (MJy sr$^{-1}$) | $\sigma$ (MJy sr$^{-1}$) |
|-------------------------|----------------------------------------|--------------------------|---------------------------------------|--------------------------|
| AFGL 2688               | 14.1                                   | 1.1                      | 0.6                                   | 0.9                      |
| OH 231.8                | 10.2                                   | 0.9                      | 0.1                                   | 0.6                      |
| IRAS 16342–3814         | 30.3                                   | 1.3                      | 0.3                                   | 0.9                      |

*Note.*—For a region of uniform background far from the source, before and after the median background removal described in the text.
As a substitute for an empirical PSF, we used OH 231.8 to sub-
tract the PSF from AFGL 2688. Figure 3b shows the result. The
residuals from using OH 231.8 as an empirical PSF appear to be
much smaller than those obtained using the model PSF, reduc-
ing the residual of 30 MJy sr$^{-1}$ to less than 10 MJy sr$^{-1}$ at 100".
Note that there are almost no PSF features, such as diffraction
spikes, remaining in Figure 3b compared to Figure 3a. How-
ever, it may be problematic to use OH 231.8 as an empirical PSF
because it may have extended emission as well, although it would
be remarkably fortuitous if both sources had extended emission
with precisely the same morphology. It is also problematic to
to scale OH 231.8 to the same surface brightness as AFGL 2688,
because in order to subtract the PSF, the whole image needs to
be scaled, thus scaling the background as well. Because AFGL
2688 is over twice as bright as OH 231.8, but the background in
AFGL 2688 is not, scaling to the level of the AFGL 2688 PSF
would overemphasize the background in OH 231.8 so that the
residuals after the PSF subtraction might be dominated by the back-
ground in OH 231.8. We can nevertheless see that the PSF sub-
traction using OH 231.8 results in residuals at a level $\sim$10 times
below that from using the model PSF at 150", which suggests
either that OH 231.8 is a point source at 70 $\mu$m or that its ex-
tended structure has the same orientation, scale, and shape as in
AFGL 2688.

The two-dimensional PSF subtraction at 160 $\mu$m was done in
a similar way using the model stinytim PSF. There are PSF fea-
tures remaining after this subtraction as well (see Fig. 3); the ends
of the diffraction spikes at 200" from the source in the original im-
age are not completely removed. We did not attempt a PSF sub-
traction of the 160 $\mu$m image of IRAS 16342$-$3814, because the
PSF of the central source is weak enough at this wavelength that
its features are below the background and the extended structures.

### Table 2

| Object                  | Mean before Subtraction (MJy sr$^{-1}$) | $\sigma$ (MJy sr$^{-1}$) | Mean after Subtraction (MJy sr$^{-1}$) | $\sigma$ (MJy sr$^{-1}$) |
|-------------------------|----------------------------------------|--------------------------|----------------------------------------|--------------------------|
| AFGL 2688               | 31.4                                   | 1.7                      | 0.3                                    | 1.5                      |
| OH 231.8                | 23.1                                   | 0.7                      | $-0.2$                                 | 0.7                      |
| IRAS 16342$-$3814       | 90.1                                   | 2.9                      | 1.0                                    | 2.3                      |

Note.—For a region of uniform background far from the source, before and after the median background removal described in the text.

In order to investigate the hypothesis of spherical shells around
a central source, we have determined an azimuthal average of the
intensity around the central source. Such an average would show
enhancements for spherically concentric shells projected as circu-
larly symmetric features from episodic mass loss during the AGB
phase. An azimuthal average also has the advantage that it greatly
reduces the parameter space necessary to fit the model PSF. The
source position and intensity are found by fitting to the brightest
Airy ring visible in our images, which is the second brightest Airy
ring of the PSF (see Fig. 2), since the source itself does not appear
in our images. The PSF Airy ring used for scaling the PSF is lo-
cated 76" from the source at 70 $\mu$m and 170" from the source
at 160 $\mu$m. We also find that the azimuthal averages provide a
subtraction with less residuals than using the two-dimensional

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Fig. 2.—Model stinytim PSFs in a log stretch to emphasize the Airy rings and diffraction spikes. Left: 70 $\mu$m PSF. Right: 160 $\mu$m PSF. The lines in the figures are 200" in length. For scale, the surface brightness of the diffraction spikes $\sim$200" from the center is $\sim$10$^{-4}$ times lower than at the center. See Figs. 3 and 5 for azimuthally averaged plots of the model PSF.
Fig. 3.—PSF-subtracted images of AFGL 2688. The color stretches are linear, with units of MJy sr$^{-1}$. The cross marks the location of the point source, while the line represents 200$''$ for scale. (a) PSF subtraction using the stinytim model PSF at 70 $\mu$m. The three PSF diffraction spikes visible in Fig. 1 appear to subtract differently, leaving different levels of residuals. (b) PSF subtraction at 70 $\mu$m using OH 231.8 as a PSF, showing almost no residuals except for the region at about 60$'$ east of north. (c) PSF subtraction using the stinytim PSF at 160 $\mu$m. The feature in the northern scan path coincides with the position of the diffraction spike in the model PSF. The images have the same orientation as Fig. 1, with north being up.

Fig. 4.—Left: PSF subtraction of OH 231.8 using the model PSF at 70 $\mu$m. The residuals are very similar to those resulting from the PSF subtraction of AFGL 2688 in Fig. 3. Right: PSF subtraction at 160 $\mu$m. The northern scan path has more structure than the eastern scan, probably from Galactic cirrus. The units of the color bars are MJy sr$^{-1}$. The cross marks the location of QX Pup, the central star of OH 231.8. North is up, as in Fig. 1.
subtraction because localized irregularities of the PSF are averaged away.

The one-dimensional PSF subtractions for AFGL 2688 at 70 μm were done using both the model PSF and OH 231.8 and are shown in Figure 5. The profiles of AFGL 2688 and OH 231.8 follow each other almost exactly out to beyond 200′′ from the source. This further indicates that OH 231.8 and AFGL 2688 are both strongly centrally concentrated at 70 μm, unless they both have exactly the same azimuthal excesses. They both also match the model PSF very well out to 100′′, beyond which both appear to have a slight excess (<1% of the extrapolated peak of the PSF), above the model PSF. Once again, this excess in the wings is more likely due to the model PSF not reproducing the wings of the actual PSFs than to the physical emission associated with the sources. At 160 μm, we only use the model PSF for subtraction because of possible contamination due to Galactic cirrus in OH 231.8.

3. RESULTS AND ANALYSIS

3.1. AFGL 2688

3.1.1. 70 μm

At 70 μm, the PSF-subtracted images of both AFGL 2688 and OH 231.8 are similar. The PSF residuals extend to about 150′′ from the source, which may be obscuring some physical extended features. However, there are no obvious circularly symmetric residuals in the PSF subtraction even with the confusion near the central source, which would be expected if there had been spherically symmetric mass loss above a dust mass-loss rate of ~2.1 × 10^{-7} M_⊙ yr^{-1} (see § 4). Previous studies with ISO by Speck et al. (2000) led to the claim of large shells around AFGL 2688 having radii of 150′′ and 300′′ on the basis of a one-dimensional scan of the Egg Nebula with ISOPHOT at 120 and 180 μm. We find, with better spatial resolution and azimuthal coverage using Spitzer, that at 70 μm there are no signs of shell-like extended emission in our field. At 150′′ from the source, the PSF subtraction residuals have a surface brightness of about 16 MJy sr^{-1} using the model PSF and about 1 MJy sr^{-1} using OH 231.8 as the empirical point source (Fig. 5). Note also that there is no discernible excess emission above the fluctuations in the background (σ ~ 0.92 MJy sr^{-1}) at 300′′ from the source.

3.1.2. 160 μm

The 160 μm image (see Fig. 3) shows roughly uniform enhanced emission to the edge of our field of view at 1000′′ from the source in the eastern scan path; the northern scan shows enhanced emission out to about 300′′, then it drops off to background.
levels. The enhanced emission in the two paths is asymmetric, as it does not fall off with distance in the eastern scan path. There does not appear to be any structure to the emission in either scan, other than that which may be attributable to the PSF diffraction spike in the north. Because the residual extended emission shows no symmetry about the central star, and because it shows no intensity fall-off in the eastern scan path, this emission most likely arises from irregularly distributed Galactic cirrus in this direction; this is supported by the relatively lower quality IRAS 100 μm image, which shows substantial extended cirrus beyond our survey region. The ISOPHOT observation of a possible shell at 300 μm was based on a 53′ × 3′ linear scan with 30′′ × 92′′ pixels, at a position angle of 8° east of north centered on the source, which in our case would be sampling the emission in the northern scan. We see with better azimuthal coverage with MIPS that the emission in both of our scans is likely strongly contaminated with Galactic cirrus. The presence of the inner shell reported by Speck et al. (2000) at 150 cannot be directly confirmed by our observations because the 160 μm PSF Airy ring at 170° from the source overlaps that region. The surface brightness at the Airy ring is about 17 MJy sr⁻¹ after background subtraction (but before PSF subtraction). This is comparable to the background-subtracted surface brightness of 20 and 30 MJy sr⁻¹ at 120 and 180 μm, respectively, reported by Speck et al. (2000).

In the azimuthally averaged surface brightness of our 160 μm image (Fig. 6), we see a result similar to that of the 70 μm data. Speck et al. (2000) reported a brightness value of the putative shell at 300° from the source of 20 MJy sr⁻¹ at 120 μm and 60 MJy sr⁻¹ at 180 μm, without background subtraction. The 120 μm emission is about 10 MJy sr⁻¹ above their background as extrapolated from the surface brightness far from the star in their plot. At 180 μm, the excess emission is about 15 MJy sr⁻¹ above the background. In the MIPS 160 μm image, we find that the surface brightness at 300° from the source is about 2 MJy sr⁻¹ after background subtraction. Although the comparison is not at the same wavelength, the excess emission we detect is 7 times below that measured by ISO. When comparing the two scans in our observations separately, we see that the eastern scan has roughly uniform brightness of 4 MJy sr⁻¹ out to 1000°, while the emission in the northern scan drops off at 400° from the source from about 2 MJy sr⁻¹ to the level we use as the background in the data reduction. Both the
asymmetry in the enhanced emission in both scans and the low surface brightness in the Spitzer data at 300 μm from the source lead us to conclude that the shell at this distance reported on the basis of ISO data is probably not associated with the source.

3.2. OH 231.8 +4.2

Neither the 70 nor 160 μm images of OH 231.8 show any signs of spherically symmetric extended emission. The PSF subtraction at 70 μm leaves residuals similar to those for AFGL 2688, although the brightnesses of these residuals are much lower because the central source is intrinsically less bright. The strongest PSF residuals are along the diffraction spikes, similar in shape to those from AFGL 2688. This further suggests that these residuals are not physical features but rather are PSF artifacts not accounted for by the stinytim model. In the 160 μm azimuthally averaged plots, both scans appear to have rather uniform emission, with the northern scan having slightly higher surface brightness at approximately 2 MJy sr⁻¹, while the eastern scan has an average surface brightness of 1 MJy sr⁻¹ (Fig. 7).

The 160 μm image shows some slightly clumpy emission along the northern scan path, slightly beyond the PSF diffraction spike (see Fig. 1) at 320°. The clumps, with a width of about 80″, have a surface brightness of about 3.6 MJy sr⁻¹ on a 2 MJy sr⁻¹ diffuse background. The IRAS 100 μm image shows diffuse Galactic cirrus in this region, which may be the origin of these clumps. They are aligned with the bipolar axis, but unfortunately also with the diffraction ray, so it may also be a PSF feature. Since this study is concerned with investigating spherically symmetric emission, we will defer the question of their nature. The azimuthally averaged surface brightness shows no enhanced emission attributable to the source (Fig. 8).

3.3. IRAS 16342–3814

In contrast to the previous two sources, IRAS 16342–3814 does show some evidence for what may be a large patchy shell at both 70 and 160 μm. The enhanced emission out to a radial distance of ~400″ is consistent with rough circular symmetry about the star in the coverage area available (Fig. 1). This radius corresponds to a physical size of about 4 pc, assuming the distance to IRAS 16342–3814 to be 2 kpc (Sahai et al. 1999). This possible shell structure is rather patchy, with a large arc in the western scan at 70 μm. At 160 μm, the same arc is present but is more diffuse. Nevertheless, the azimuthal average shows an excess above the background at ~400″ from the central source. The brightest portion of this feature occurs at a position angle of 250° east of north, which is the same direction as the axis of the bipolar nebula seen in the optical. The ratio of the 70 to 160 μm average surface brightness is roughly constant (~0.3) as a function of radial distance from the source. This ratio yields a color temperature of ~32 ± 2 K and, if a ν¹ emissivity law is assumed, a dust
temperature of 26 ± 2 K. The constant color temperature suggests that the dust is heated primarily by the interstellar radiation field.

Because there are a number of interstellar cirrus features in the general direction of IRAS 16342–3814, we cannot definitively argue that the patchy arc of emission in the scan paths around this source is caused by mass loss from the star. The IRAS 100 μm image of this region with an overlay of the coverage of our data (Fig. 9) shows that there is indeed a substantial likelihood that this emission is cirrus. With this caveat in mind, we proceed in the analysis below on the assumption that the extended emission has resulted from mass loss from the star to obtain some indicative numbers for the mass-loss rate necessary to produce such a shell. In the following analysis, we use the term “mass outflow rate” to indicate the total mass flowing outward per unit time across a spherical shell at a particular radius; this includes both the stellar component and the ISM being swept up. We use the term “mass-loss rate” to refer to mass loss from only the star.

Making a few assumptions about the mass outflow and the dust, we can set some limits on the mass outflow rate of IRAS 16342–3814. Assuming that the mass loss is spherically symmetric, we can fit a model of the expected brightness profile to the observed radial profile of the source. Figures 10 and 11 show the azimuthally averaged radial profiles at 70 and 160 μm, respectively. We fit only the 70 μm radial profile because there is less contamination by Galactic cirrus compared to 160 μm. Following the derivation by Gillett et al. (1986), if we assume a $1/r^2$ density profile,
appropriate for constant mass outflow, where $r$ is the distance from the star, and a constant expansion velocity, $v_e$, then the surface brightness $I(b)$ has the form

$$I(b) = \frac{\dot{M} \kappa_v B_{\nu}(T)}{2\pi v_e b} \cos^{-1} \left( \frac{b}{R_{\text{max}}} \right) \text{ for } R_{\text{min}} \leq b \leq R_{\text{max}},$$

$$I(b) = \frac{\dot{M} \kappa_v B_{\nu}(T)}{2\pi v_e b} \left[ \cos^{-1} \left( \frac{b}{R_{\text{max}}} \right) - \cos^{-1} \left( \frac{b}{R_{\text{min}}} \right) \right] \text{ for } b < R_{\text{min}},$$

where $b$ is the projected physical distance from the source in the sky, $\kappa_v$ is the opacity coefficient in units of cm$^2$ g$^{-1}$, $B_{\nu}(T)$ is the blackbody function, and $R_{\text{max}}$ and $R_{\text{min}}$ are the outer and inner radii of the shell. We further assume that the outflow velocity is constant at 15 km s$^{-1}$ and that the dust is composed of small astronomical silicate grains with $\kappa_v = 104$ cm$^2$ g$^{-1}$ at 70 $\mu$m (using $a = 0.1$ $\mu$m, $\rho = 2.3$ g cm$^{-3}$, and $Q_{\text{abs}} = 2.99 \times 10^{-3}$ from Draine & Lee 1984). We also adopt a constant temperature of 26 K throughout the shell and envelope. Figure 12 gives a comparison between different models having various mass outflow rates. The best-fit model is a shell with a 4.2 pc radius and a thickness of 1 pc, with a dust outflow rate of $1.5 \times 10^{-6} M_\odot$ yr$^{-1}$ imposed on a smooth envelope with a constant dust outflow rate of $1.5 \times 10^{-7} M_\odot$ yr$^{-1}$. This implies a rather high gas outflow rate on the order of $3 \times 10^{-4} M_\odot$ yr$^{-1}$ in the shell and $3 \times 10^{-5} M_\odot$ yr$^{-1}$ in the smooth envelope, assuming a gas-to-dust mass ratio of 200. Using OH 231.8 as the empirical PSF, the fit only requires a shell component with a mass outflow rate of $3 \times 10^{-4} M_\odot$ yr$^{-1}$ without an underlying smooth envelope. These fits depend on the choice of PSF, but once the PSF is chosen, the mass outflow rates are insensitive to residuals from PSF subtraction, since we only fit for the region beyond 150 $\arcsec$ from the central source (see Fig. 10). However, our value for the mass outflow rate is highly dependent on the assumed temperature of the dust. For typical ISM dust temperatures between 22 and 35 K, the inferred dust outflow rate is related empirically to the adopted temperature by $\dot{M} \propto T^{-7.6}$ at 70 $\mu$m. If $T > 26$ K, we would infer a substantially lower mass outflow rate.

Given the model thickness of the shell and assuming a typical expansion velocity of 15 km s$^{-1}$, we estimate the maximum duration of the enhanced mass-loss event which produced the shell to be about 65,000 yr. This is an upper limit because the internal velocity dispersion in the shell broadens the shell as it expands. A 1 km s$^{-1}$ dispersion, for example, would reduce the duration of the mass loss that produced the shell by about one-third. If we
use an age of 40,000 yr for the duration of the enhanced mass loss and approximate the shell as spherical, the total dust mass would be about $0.04 M_\odot$, giving a total shell mass of $\sim 8 M_\odot$, assuming a gas-to-dust mass ratio equal to 200. The velocity of the shell is probably slower than the molecular outflow velocity of a typical AGB star, and the total amount of mass lost by the AGB star is likely smaller than this amount because of the interaction with the ISM out to the distances we are observing (see below).

The mass of the shell can be estimated directly from the infrared emission using the equation $M = F_\nu D^2 / [(B_\nu(T) \kappa_\nu)]$, where $F_\nu$ is the total flux density in the shell and $D$ is the distance to the source. The integrated flux density from the limited azimuthal coverage that we have between radii of 300" and 400" is 6.4 Jy at 70 \textmu m, corresponding to a dust mass of 0.015 $M_\odot$ in our observed portion of the shell, assuming a temperature of 26 K for the dust. We have about one-fifth of the full azimuthal coverage with data at this distance from the star, and we can estimate the total dust mass of the shell if we approximate the shell as isotropic with an average surface brightness of 2.5 MJy sr$^{-1}$ at 70 \textmu m from the radial profile, with a width of 100" and a temperature of 26 K. The total dust mass of the extrapolated shell is then about 0.03 $M_\odot$, comparable to the above estimate.

Because the shell is so large, the amount of interstellar matter that may have been swept up and accumulated in the shell during the AGB could be significant. For an ISM hydrogen density of 1 cm$^{-3}$, a 4 pc radius shell would have swept up about 7 $M_\odot$, which would account for almost all the mass we may be measuring. The accumulation of interstellar material could potentially lower the stellar mass-loss rate estimated from our model by a large factor. We therefore emphasize that the mass outflow rate estimate is only an upper limit to the stellar mass-loss rate.

One of the difficulties in addressing the mass-loss history of IRAS 16342−3814 with the current data is its location in the Galaxy; with a scale height of only 150 pc, there is possible confusion with diffuse Galactic cirrus. An unfortunate alignment with background emission is an alternative to the existence of a shell produced by mass loss. Further observations with better azimuthal coverage are needed to test the circumstellar-shell hypothesis.

### 4. DISCUSSION

The extended dust emission in AFGL 2688 and OH 231.8 seems to show that these two objects do not have as long a mass-loss history as one might have anticipated. Our results for these two sources probe the region beyond $\sim 100$" from the central star, which corresponds to $1.0 \times 10^4$ yr ago for AFGL 2688 and $2.8 \times 10^4$ yr ago for OH 231.8, given a distance of 420 pc (Ueta et al. 2006) and 1.2 kpc (Jura & Morris 1985), respectively, and an
The solid lines show the expected surface brightness for a smooth constant mass-loss envelope with a radius of 4.2 pc, while the dashed lines show the radial profile of a single shell of 1 pc thickness at the same mass-loss rate. The diamonds show a model PSF is a two-component model with a shell of radius 4.2 pc and thickness 1 pc requiring a dust mass-loss rate of $10^{-6} \ M_{\odot}\ yr^{-1}$ superimposed on an envelope from a constant dust mass-loss rate of $10^{-7} \ M_{\odot}\ yr^{-1}$ (dashed blue line). The asterisks show that the radial profile found from using OH 231.8 as a substitute for the model PSF in the PSF subtraction will fit using only the shell component with a dust mass-loss rate of $10^{-7} \ M_{\odot}\ yr^{-1}$ (dashed orange line). Points closer than a radial distance of $\sim 150^\circ$ are unreliable because they are most affected by PSF subtraction residuals and are not used in the fit.

The dust mass-loss rate can be simplified as a function of the observed surface brightness $I$ and the projected distance from the source in the sky with the assumption that $b \ll R_{\text{max}}$,

$$M(70 \ \mu m) \sim 3.8 \times 10^{-8} \ M_{\odot}\ yr^{-1}$$

$$\left( \frac{I_{70 \ \mu m}}{1 \ \text{MJy sr}^{-1}} \right) \left( \frac{100 \ cm^2 \ g^{-1}}{\kappa_{70 \ \mu m}} \right) \left( \frac{b \ \text{pc}}{1 \ \text{pc}} \right)$$

$$\times \left( \frac{v_e}{15 \ km \ s^{-1}} \right) \left( \frac{T}{30 \ K} \right)^{-7.6}$$

$$M(160 \ \mu m) \sim 2.9 \times 10^{-8} \ M_{\odot}\ yr^{-1}$$

$$\left( \frac{I_{160 \ \mu m}}{1 \ \text{MJy sr}^{-1}} \right) \left( \frac{20 \ cm^2 \ g^{-1}}{\kappa_{160 \ \mu m}} \right) \left( \frac{b \ \text{pc}}{1 \ \text{pc}} \right)$$

$$\times \left( \frac{v_e}{15 \ km \ s^{-1}} \right) \left( \frac{T}{30 \ K} \right)^{-3.6}$$

If $b \sim R_{\text{max}}$, then the full form of equation (2) must be used because the $\cos^{-1}(b/R_{\text{max}})$ term in the denominator of equation (2) becomes important and will cause the dust mass-loss rate inferred from a given surface brightness value to increase drastically. For cases such as AFGL 2688 and OH 231.8, where we do not see a clear envelope associated with the source, we cannot be sure that the condition $b \ll R_{\text{max}}$ holds, since $R_{\text{max}}$ is indeterminate. The equations above also show the temperature dependence in the form of a power law to approximate the blackbody function between 22 and 35 K. From these equations we see that the temperature dependence at 160 $\mu$m is less steep than at 70 $\mu$m, but the contamination by Galactic cirrus near the sources makes estimating upper limits problematic at 160 $\mu$m. We can establish an upper limit to the mass-loss rates for AFGL 2688 and OH 231.8 at 70 $\mu$m based on the surface brightness of the residual left from the PSF subtraction at 200” from the source, which is a compromise between a location far enough from the source that PSF subtraction errors are small and a location close enough to the source that there could plausibly be a circumstellar envelope. For AFGL 2688, 200” corresponds to a radial distance from the source of 0.4 pc, using a distance to the source of 420 pc (Ueta et al. 2006). The surface brightness after PSF subtraction with the model PSF is about 14 MJy sr$^{-1}$ at 70 $\mu$m. Assuming an expansion velocity of 20 km s$^{-1}$ as observed in CO by Skinner et al. (1997), a dust temperature of 30 K, $\kappa_{\nu} = 104 \ cm^2 \ g^{-1}$ appropriate for carbon dust (Draine & Lee 1984), and that the possible envelope has a radius significantly greater than 0.4 pc, the dust mass-loss rate upper limit is 2.1 $\times$ 10$^{-7} \ M_{\odot}\ yr^{-1}$. Similarly for OH 231.8, the residual emission from the PSF subtraction is 3 MJy sr$^{-1}$ at 200” from the central star, which corresponds to 1.3 pc at a distance of 1.3 kpc. This surface brightness implies a dust mass-loss rate of $1.0 \times 10^{-7} \ M_{\odot}\ yr^{-1}$, assuming an outflow velocity of 15 km s$^{-1}$, $\kappa_{\nu} = 98 \ cm^2 \ g^{-1}$ (appropriate for silicate dust), and a temperature of 30 K.

There are several potential explanations for the lack of extended emission seen in this study. One is that even with Spitzer’s increased sensitivity, the dust emission is below the threshold for detection. Since the distances we are studying are far from the central star, we would expect the temperature of the dust to be determined by the ambient interstellar radiation field. If the dust temperature is about 20 K, typical for the ISM (Mathis et al. 1983), and an emissivity $\propto \nu^{\alpha}$, the surface brightness would be 12 times stronger at 160 $\mu$m than at 70 $\mu$m, where the resolution and sensitivity of MIPS is better. We would be more likely to detect cool dust emission at 160 $\mu$m than at 70 $\mu$m. However, confusion with Galactic cirrus is also likely at 160 $\mu$m because it is about the same temperature as any hypothetical extended dust emission associated with the source that is heated primarily by the interstellar radiation field. For comparison, our detection of the possible shell from IRAS 16342−3184 has a ratio of $I_{160 \ \mu m}/I_{70 \ \mu m}$ similar to 3.3, corresponding to a color temperature of 32 K, which requires a higher than average interstellar radiation field.

The upper limits to the mass-loss rates derived in this study can be compared with theoretical AGB evolutionary models, particularly those that predict enhanced mass-loss rates due to thermal pulsation near the end of the AGB. The spatial coverage in this study, between ~200” and 1000” from the central star, translates into a probe of the history of mass loss between 2 × 10$^4$ and 1 × 10$^5$ yr ago for AFGL 2688 and 6 × 10$^4$ and 3 × 10$^5$ yr ago for OH 231.8, using an expansion velocity of 20 km s$^{-1}$ for both sources. The models by Vassiliadis & Wood (1993) show that for a 2.0 $M_{\odot}$ progenitor, during the last few × 10$^5$ yr of AGB evolution, there are several thermal pulses which result in enhanced mass-loss rates peaking at about 1.3 × 10$^{-5} \ M_{\odot}\ yr^{-1}$ during the end of each pulse. Using a gas-to-dust mass ratio of 200, we find that for AFGL 2688 and OH 231.8, the upper limit to the total mass-loss rate during the above time intervals is about 4 × 10$^{-5}$ and 2 × 10$^{-5} \ M_{\odot}\ yr^{-1}$, respectively. These limits are close to the sensitivity necessary to see shells that may be the result of thermal pulsation on the AGB. Although we do not detect the shells reported by Speck et al. (2000), which they attribute to thermal pulses, the signatures of thermal pulses may still be present but below our current sensitivity.
We also consider the possibility that OH 231.8 does not show extended emission in the far-infrared because of interactions with a binary companion, which caused the central star to lose mass more rapidly and more recently than during the evolution of a lone AGB star. A companion to QX Pup (the central star of OH 231.8) is evidenced by optical spectra consistent with a companion of stellar type A0 V (Sánchez Contreras et al. 2004). QX Pup also shows the peculiar paradox of being an M9 III (Cohen 1981) AGB star while its bipolar activity and morphology display all the signs of post-AGB activity of typical PPNe. Having a close companion would enhance the mass-loss rate and provide a mechanism for generating the bipolar outflows (Morris 1987), thus shortening its mass-loss history enough that we should not be surprised to see no emission far from the source. In contrast to the collimated outflow from OH 231.8 (Alcolea et al. 2001), AFGL 2688 has a spherically symmetric envelope seen in 13CO (Yamamura et al. 1996) and evidenced by the partial, concentric, circular arcs present in HST images (Sahai et al. 1998). Since a binary interaction would not cause the past spherically symmetric mass loss, a possible companion is probably not a good explanation for initiating mass loss, although the present bipolar morphology of AFGL 2688 is consistent with the possibility that a binary interaction has altered the mass loss in more recent times.

Tracing the mass-loss history during the AGB phase should be relatively straightforward via mapping the emission from the circumstellar envelope. But in practice it has been difficult, because molecular-line observations are ultimately limited by the photodissociation of molecules in the outer envelope regions, and far-infrared observations of dust emission have been limited by the generally low angular resolution of the space-based telescopes which have been available for this purpose in the past (IRAS and ISO). Hence, the reported detections of very extended emission in a few dying stars with IRAS and ISO have generally been recognized as an important milestone in the study of mass loss. However, such detections have also raised the very important question of why only a few select objects, such as Y CVn (Izumiura et al. 1996) or RY Dra (Young et al. 1993), which are not particularly known for having high mass-loss rates, show extended envelopes, whereas large numbers of stars with high CO-determined mass-loss rates do not reveal the presence of such envelopes. Is this because the radial density law for most of these high mass-loss stars is significantly steeper than in objects like Y CVn or RY Dra, and in particular steeper than \( r^{-2} \) (an issue of profound importance for the evolutionary times of stars through the AGB phase and theories of mass loss), or are the claimed detections of extended envelopes really a result of poorly characterized instrumental artifacts? The Spitzer data presented in this paper clearly show that the presence of these shells cannot be confirmed at a level well below the intensities expected from Speck et al.’s (2000) results. Our nondetections call into question not only the ISO results on AFGL 2688 but all results on the detection of extended envelopes in other objects using the same linear scan technique described by Speck et al. More detailed mapping of many high mass-loss rate objects like AFGL 2688 is crucially needed to search for such shells.

5. SUMMARY

Spitzer observations of extended envelopes of expanding, dusty outflows from bipolar AGB and post-AGB stars reveal that there may be a very large dust shell with a radius of 400" around IRAS 16342–3814. The combination of the presence of nearby cirrus emission and limited azimuthal coverage in the images makes the conclusion of a shell uncertain, but if the shell is indeed the result of an episodic mass-loss event, then it would represent one of the largest dust shells found so far.

Our observations of AFGL 2688 at 70 \( \mu \)m do not show the dust shells at 150" and 300" from the source reported by Speck et al. (2000). Since the dust shell may be very cool, the nondetection at 70 \( \mu \)m does not alone rule out dust shells. However, we find that there is only a slight excess at 160 \( \mu \)m of 2 MJy sr\(^{-1}\) above the background at the reported location of the outer shell (\( \sim 300" \)). With greater azimuthal coverage than was previously obtained with ISOPHOT we find that there is substantial contamination by Galactic cirrus in the region at 160 \( \mu \)m, with Galactic cirrus emission above the sky background present throughout the entire eastern scan path of our observations. Unfortunately, at 160 \( \mu \)m we can only set an upper limit on the emission from a dust shell at 150" from the source because one of the Airy rings of the PSF overlaps that region. We also see no extended emission from OH 231.8 at either 70 or 160 \( \mu \)m other than that attributable to Galactic cirrus. In fact, using OH 231.8 as an empirical point source for PSF subtraction from AFGL 2688 at 70 \( \mu \)m appears to substantially reduce PSF subtraction residuals compared to using the model PSF.

The limitation of our method of observation is that we have only two radial directions to probe possible extended emission. For cases like IRAS 16342–3814, where the shell is patchy, better azimuthal information would help to resolve whether the origin of the emission is from the star or from Galactic cirrus. The MIPS data show that observing very extended emission in the far-infrared is possible but difficult because of the prominence of Galactic cirrus emission at these wavelengths.

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