AN EXPANDED VERY LARGE ARRAY AND CARMA STUDY OF DUSTY DISKS AND TORII WITH LARGE GRAINS IN DYING STARS

R. Sahai, M. J. Clausen, S. Schnee, M. R. Morris, and C. Sánchez Contreras

1. INTRODUCTION

Ordinary stars (i.e., with main-sequence masses 1–8 $M_\odot$) die extraordinary deaths, producing profound effects on their environment before they fade into obscurity as white dwarfs. The mass-loss phenomena in these objects play a key role in the Galaxy’s chemical and dynamical evolution, and dramatically alter stellar evolution. Post-asymptotic giant branch (pAGB) objects are believed to be objects in transition between the AGB and planetary nebula (PN) evolutionary phases and hold the key to some of the most vexing problems in our understanding of these very late stages of evolution for ordinary stars.

We have made considerable progress in understanding the mass-loss processes which govern the transformation of the spherical mass-loss envelopes of AGB stars into strikingly aspherical PNs (Balick & Frank 2002; Sahai et al. 2011), specifically with the identification of fast, collimated outflows as the most likely primary agents for the change in morphology (Sahai & Trauger 1998). But the presence of dusty disks (or highly flattened equatorial structures) around pAGB stars remains an enigma: an intriguing feature of these pAGB objects is the presence of strong submillimeter (submm) excesses, which suggest the presence of very large, cold grains. Here we report observations that confirm the presence of very large grains in dusty disks and torii around the central stars in a small sample of post-asymptotic giant branch (pAGB) objects, as inferred from millimeter (mm) and submillimeter (submm) observations. Supporting mm-wave observations were also obtained with the Combined Array for Research in Millimeter-wave Astronomy toward three of our sources. Our EVLA survey has resulted in a robust detection of our most prominent submm emission source, the pre-planetary nebula (PPN) IRAS 22036+5306, in all three bands, and the disk-prominent pAGB object, RV Tau, in one band. The observed fluxes are consistent with optically thin free–free emission, and since they are insignificant compared to their submm/mm fluxes, we conclude that the latter must come from substantial masses of cool, large (mm-sized) grains. We find that the power-law emissivity in the cm-to-submm range for the large grains in IRAS22036 is $\nu^\beta$, with $\beta = 1–1.3$. Furthermore, the value of $\beta$ in the 3–0.85 mm range for the three disk-prominent pAGB sources ($\beta \lesssim 0.4$) is significantly lower than that of IRAS22036, suggesting that the grains in pAGB objects with circumbinary disks are likely larger than those in the dusty waists of pre-planetary nebulae.

Key words: accretion, accretion disks – binaries: general – circumstellar matter – radio continuum: stars – stars: AGB and post-AGB – stars: mass-loss

1. INTRODUCTION
the latter indicate the presence of large grains as in the dpAGB objects. For example, in the bipolar PPN IRAS 22036+5306, Sahai et al. (2006) find an unresolved (<0′′0.85) submm continuum source associated with the central, dusty torus seen in HST images (Sahai et al. 2003). Modeling of the full SED, including the submm flux, shows that the latter is produced by a very sub-stellar mass (≥0.02 $M_\odot$) of large (mm-sized), cool ($T \lesssim 50$ K) grains. Similar results have been inferred for other PPNs, e.g., IRAS 18276–1431 and IRAS 19475+3119, from Owens Valley Radio Observatory (OVRO) 2.6 mm data (Sánchez Contreras et al. 2007; Sahai et al. 2007b), and CRL 2688 from Very Large Array 1.3–3.6 mm data (Jura et al. 2000).

The connection between dusty waists in PPNs, the disks in dpAGB objects, and inner accretion disks is unknown. Yet, these structures appear to be key ingredients in our understanding of the late evolution of most stars—the inner disks are the only ones that are likely to be able to contribute to jet production, while the dusty waists are the only ones that contribute to the observed morphologies in PPNs. It is believed that accretion disks may form from either (1) the shredding of a low-mass companion around an AGB primary core (Reyes-Ruiz & Lopez 1999) or (2) Bondi–Hoyle accretion of the primary wind around the companion (Morris 1987; Soker & Livio 2004). Smoothed-particle hydrodynamics (SPH) codes have demonstrated how an unbound outflow from a mass-losing primary can be concentrated toward the system’s equatorial plane into a small, ∼(1 to few) AU, bound disk around a binary companion (Mastrodemos & Morris 1998). The Red Rectangle (HD 44179), which is the closest known PPN with a binary central star, provides a connecting link between these two classes of PAGB objects—direct evidence for a large (outer radius ∼300–500 AU), bound disk in this object comes from interferometric CO(2–1) mapping (Bujarrabal et al. 2005), and HST imaging reveals a bipolar PPN (Cohen et al. 2004). The disk or torus mass can provide an important constraint on the formation process. For example, common envelope evolution (Nordhaus & Blackman 2006) would lead to expulsion of most of the stellar envelope. Hence, a large value of the disk or torus mass (∼0.01 $M_\odot$ in dust), as, e.g., in IRAS22036, would support a common envelope origin; wind accretion would lead to much lower values for this mass (as, e.g., found in HD 44179). However, since the frequent detection of strong Hα emission (e.g., Maas et al. 2005; Sánchez Contreras et al. 2008) in pAGB objects shows that some ionized gas is typically present, the contribution of free–free emission from ionized gas to the submm/mm fluxes must be determined before reliable masses can be observed. Furthermore, the dust power-law emissivity index in the mm-to-cm wavelength range is poorly known. In order to address both these issues, we carried out a pilot multifrequency (43.3, 33.6, and 8.5 GHz) survey of 10 pAGB objects with the National Radio Astronomy Observatory’s Expanded Very Large Array (EVLA) facility and report our results in this Letter.

### 2. OBSERVATIONS

We selected 10 pAGB objects (Table 1) for EVLA observations on the basis of their published mm or submm continuum fluxes (e.g., Gledhill et al. 2001; Gürtler et al. 1996) and a new interferometric survey with OVRO (Sánchez Contreras & Sahai 2011) and the Combined Array for Research in Millimeter-wave Astronomy (CARMA; reported in this Letter).

The EVLA observations were performed with the array in the D configuration in a series of short scheduling blocks under project code AS1021, from 2010 March 26 through 2010 June 21. The EVLA WIDAR correlator was configured to give two subbands each with a bandwidth of 128 MHz and dual polarization. Three frequency bands were observed for most sources (though not all, because of time constraints) with center frequencies of 8396 and 8524 MHz (X band), 33496 and 33624 MHz (Ka band), and 43216 and 43344 MHz (Q band). Observations in the higher frequency bands typically

### Table 1

| Source                  | $X_{\mu Jy(\sigma)}$ | $K_a_{\mu Jy(\sigma)}$ | $Q_{\mu Jy(\sigma)}$ | $3\,mm^a$ mL(y(σ)) | $1.3\,mm^b$ mL(y(σ)) | $0.85\,mm$ mL(y(σ)) | $D^c$ (kpc) | $M_d$ ($10^{-2}\,M_\odot$) |
|------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|--------------------------|------------|--------------------------|
| RV Tau                 | ...                    | 270 (50)               | (107)                  | 3.9 (0.2)               | ...                     | 50.3 (3.6)^d             | 2.2        | 0.1                      |
| U Mon                  | ...                    | (100)                  | (169)                  | 15 (0.3)                | 100 (14)                | 182 (2.6)^d              | 0.77       | 0.064                    |
| AC Her                 | (46)                   | ...                    | ...                    | 4.6 (0.4)               | 38 (1)                  | 99.4 (3.8)^d             | 1.1        | 0.072                    |
| IRAS16342–3814         | (162)                  | ...                    | (254)                  | ...                     | 277 (13)^f              | 602 (90)^f               | ...        | ...                      |
| IRAS17150–3224         | (168)                  | ...                    | ...                    | 158 (10)^f              | ...                     | ...                      | ...        | ...                      |
| IRAS18135–4156         | (66)                   | (82)                   | (169)                  | 12 (1.4)^g              | ...                     | ...                      | ...        | ...                      |
| IRAS18276–1431         | (108)                  | (157)                  | ...                    | 11 (3.2)^g              | ...                     | ...                      | ...        | ...                      |
| IRAS19548+3035         | (45)                   | ...                    | ...                    | 6 (1.1)^g               | ...                     | ...                      | ...        | ...                      |
| IRAS20000+3329         | (44)                   | ...                    | ...                    | 6 (1.1)^g               | 11.4(1.7)^h             | 30.9 (2.5)^i             | ...        | ...                      |
| IRAS22036+5306         | 1010 (62)              | 1180 (55)              | 1230 (81)              | 8.4 (0.7)^j             | ...                     | 290 (40)^j               | 2          | 2.2                      |

### Notes.

a Beam sizes for RV Tau, U Mon, and AC Her 3 mm observations are 2′′4 × 1′′5, 2′′4 × 2′′1, and 2′′4 × 1′′5, respectively.

b Beam sizes for U Mon and AC Her 1.3 mm observations are 2′′2 × 0′′9 and 2′′0 × 1′′8, respectively.

c Distances for RV Tau, U Mon, and AC Her from de Ruyter et al. (2005) and for IRAS22036 from Sahai et al. (2003).

d de Ruyter et al. (2005).

e Gürtler et al. (1996).

f Ladjal et al. (2010); central wavelength 0.87 mm.

g Sánchez Contreras & Sahai (2011); central wavelength 2.6 mm.

h Bueni et al. (2007); central wavelength 1.2 mm.

i Gledhill et al. (2002).

j Sahai et al. (2006); central wavelengths 2.6 mm and 0.88 mm.

k Jura et al. (2000).
had more time on source in order to have similar signal-to-noise ratios in all three bands. For low-declination sources, however, the increase in the rms noise levels for the two high-frequency bands is still apparent. The synthesized beam sizes depend upon the receiver band as well as the declination: they range from $8''2 \times 2''5$ to $33''3 \times 20''9$ for X band, $2'2 \times 1'8$ to $9'5 \times 1'8$ for $Ka$ band, and $1''5 \times 1'4$ to $6'2 \times 1'7$ at $Q$ band, depending upon the declination.

Absolute flux calibration was determined by observing either 3C286 or 3C48, which are EVLA flux-density standards. The flux density scale is likely accurate to within 5% for $Q$ band, high-declination sources, but degrades to 20%–30% for $Q$ band, and especially the low-declination sources. The gain (phase and amplitude) calibration was carried out in the normal manner after initial bandpass and delay calibration were made using the flux-density calibrators. All calibration and imaging steps were performed using natural weighting with the AIPS software package; fluxes were derived from Gaussian fits to the observed intensity maps, using the IMFIT task.

Observations with CARMA, a 15-element interferometer with nine 6.1 m dishes and six 10.4 m dishes, covered the three $dpAGB$ objects: AC Her, U Mon, and RV Tau with $\sim(2$–$3')\circ$ resolution; AC Her and U Mon were observed at 3 and 1.3 mm whereas RV Tau was observed at 3 mm only. Each source was observed in single pointings, with 15–20 minutes spent on source and 3–5 minutes spent on the calibrator in each observing cycle. A passband calibrator was observed in each track, and pointing was done every 2–3 hr for the 1 mm observations and at the beginning of each 3 mm track. Absolute flux calibration was done using the gain and passband calibrators in the continuously updated CARMA flux catalog, supplemented by observations of primary flux-density calibrators in those tracks in which such a source was available. Based on the repeatability of the quasar fluxes, we believe that our source fluxes are accurate to within ±20%. Calibration and imaging was done using the MIRIAD data reduction package, using natural weighting and the standard clean algorithm; fluxes were derived from Gaussian fits to the observed intensity maps, using the IMFIT task. Some of the 1.3 mm observations were taken in shared-risk time in which only the nine 6.1 m antennas were in the array.

3. RESULTS

We detected two objects with the EVLA: IRAS22036 was detected in all three bands, whereas RV Tau was detected in the $Ka$ band only (Table 1). For IRAS22036, the fluxes vary only weakly over the wavelength range covered by the $X$, $Ka$, and $Q$ bands, i.e., from $3.5$ to $0.67$ cm (Table 1), implying that these arise predominantly from optically thin free–free emission. If, for the emitting region, we assume a typical ionized gas temperature of $10^{4}$ K, and a cylindrical geometry with a length along the line of sight equal to its projected lateral extent, then the observed free–free flux, $S_{\nu}$, is a function of $\theta_{\text{ff}}$ (source angular size), $n_{e}$ (the electron density, assumed to be uniform), and $\nu$. Thus, from the observed 33.6 GHz flux we derive a free–free optical depth of $\tau_{ff}(33.6 \text{GHz}) > 0.0002$ and $n_{e} > 1.1 \times 10^{6}$ cm$^{-3}$, assuming that $\theta_{\text{ff}} \approx 0''.85$ (i.e., the upper limit for the size of the submm continuum source). By requiring $\tau_{ff}(8.5 \text{GHz}) < 1$, the observed 8.5 GHz flux implies $n_{e} < 6.4 \times 10^{5}$ cm$^{-3}$ and $\theta_{\text{ff}} > 0.0067$ (130 AU); the $\nu^{-2.1}$ dependence of $\tau_{ff}$ implies $\tau_{ff}(33.6 \text{GHz}) < 0.055$. The free–free emission is unlikely to arise from an ionized outflow as it would produce a spectral variation $S_{\nu} \propto \nu^{0.8}$ (Wright & Barlow 1975).

For RV Tau (not observed in X band), our $Ka$-band detection and $Q$-band upper limit ($107 \mu$Jy) are inconsistent with optically thick free–free emission and thermal dust emission, as these produce a spectral index, $\alpha = d \ln S/d \ln \nu \geq 2$, implying a $Q$-band free–free flux $S_{Q}(0.67\text{cm}) \geq 490 \mu$Jy, if scaled from the $Ka$-band flux. For optically thin free–free emission, with $\alpha \approx -0.1$, we expect $S_{Q}(0.67 \text{cm}) = 262 \pm 50 \mu$Jy, consistent with our 3σ upper limit of 321 μJy.

Millimeter-wave continuum emission was detected in the three sources observed with CARMA: AC Her, U Mon, and RV Tau (Table 1), and was unresolved (beam sizes were typically $\leq 2''$), consistent with these arising in a compact structure, likely a disk, rather than an extended outflow.

If we scale the radio-to-mm/submm flux ratios of IRAS22036 for PPNs and RV Tau for $dpAGB$ objects, we find that the expected radio fluxes for several $pAGB$ objects ($Ka$-band flux $= 2.45, 1.68, 1.54$, and $1.04$ mJy, respectively, for IRAS16342, 18135, 18276, and U Mon; $X$-band flux $= 7.21$ mJy for IRAS19548, 20000) are far above their observed upper limits (Table 1). This result supports the idea that the physical mechanism predominantly responsible for the radio emission in $pAGB$ objects is unrelated to that responsible for the mm/submm emission.

Since the observed EVLA fluxes in IRAS22036 and RV Tau are insignificant compared to their submm/mm fluxes, the latter cannot be due to free–free emission and must be due to thermal emission from grains, thus providing strong support for the presence of substantial masses of cool large grains in these objects. Given the very low estimated free–free optical depth in IRAS22036, we extrapolate the observed $X$-band flux using a spectral index of $-0.1$ to estimate the free–free flux in the $Ka$ and $Q$ bands of 880 and 856 μJy—the excess fluxes of 300 and 374 μJy above the free–free extrapolated emission in these bands must then represent the long-wavelength tail of the large grain emission seen in the submm–mm wavelength range. In Figure 1, we show the full SED of IRAS22036, together with the dust radiative transfer model of Sahai et al. (2006), which includes a component of cold (50 K), large ($a = 1$ mm) grains. The model, which uses the DUSTY code (Ivezic et al. 1999) and optical constants for silicate dust provided by Ossenkopf et al. (1992), was constrained by the long-wavelength emission up to 2.6 mm—we find that it reproduces the excess $Q$-band flux of 374 μJy, but the predicted $Ka$-band flux is a factor 3.7 times lower than our value of the excess, 300 μJy. This is likely due to the inadequacy of the current dust optical constants for computing dust emissivity at cm wavelengths. We have therefore made new optimally thin dust model fits to the SED from 0.88 mm to 0.67 cm, using the Rayleigh–Jeans ($R$–$J$) approximation and a power-law dust emissivity, $\kappa(\nu) \propto \nu^{\beta}$, and find that values of $\beta$ in the range 1–1.3 provide an adequate fit (Figure 1, inset).

We find that $\beta = 0$ for RV Tau in the 3–0.85 mm wavelength range (computed in the $R$–$J$ approximation), significantly lower than the corresponding value ($\beta = 1.3$) for IRAS 22036 (over the same wavelength range). If we assume that, like RV Tau, the other two $dpAGB$ objects, U Mon and AC Her, also do not have significant free–free contributions at mm/submm wavelengths, then their 3–0.85 mm flux ratios yield similarly low values of $\beta$ (0 and 0.4, respectively). This difference suggests that the grains in the disks of $dpAGB$ objects are likely larger than those in the dusty waist of IRAS 22036, and may be several mm in size: e.g., Draine (2006) finds that, for the standard power-law distribution of grain sizes that characterizes interstellar dust and that may apply to particles growing by agglomeration in protoplanetary
disks, $\beta \lesssim 1$ (at $\lambda \sim 1$ mm) results when grains grow to sizes $a \geq 3$ mm.

We estimate the mass of the large grains ($M_d$) for the four sources in Table 1 for which the observed submm flux is known to come from a compact central source, i.e., the three dpAGB sources and IRAS22036, by using the R–J approximation for grains emitting at wavelength $\lambda$, $M_d = (S_\nu \lambda^2 D^2)/(2 k T_d \chi_\nu)$, where $D$ is the source distance and $\chi_\nu$ is the dust opacity (per unit dust mass). We have not estimated dust masses for the six sources in Table 1 for which we are unable to associate the observed mm/submm fluxes with a central dusty torus (all of which are PPNs), either because the mm/submm observations lack adequate angular resolution (IRAS16342, 17150, 18135, 18276, 20000), or because there is lack of optical imaging to inform us of the object’s morphological structure (IRAS19548).

The value of $\chi_\nu$ at submm wavelengths is uncertain by at least a factor of a few, and likely more. In the extensive study of the composition and radiative properties of grains by Pollack et al. (1994, hereafter Petal94), only large grains with $a \geq 3$ mm have values of $\beta \lesssim 1.3$ in the 650 $\mu$m to 2.7 mm wavelength range. If we use the largest values of $\chi_\nu$ estimated for such grains from this study, then setting $\chi_\nu(1 \text{ mm})$ equal to $g_{d_k} \kappa_{\nu}$, where $g_{d_k} = 71.4$ is the gas-to-dust ratio estimated from Table 2 of Petal94, and $\kappa_{\nu} = 7.4 \times 10^{-3}$ and $\beta = 1.34$ are taken from Table 4 of Petal94, we extrapolate $\chi_\nu(1 \text{ mm})$ to obtain $\chi_\nu(0.85 \text{ mm}) = 0.65 \text{ cm}^2 \text{ g}^{-1}$. There are no grains in the Petal94 study with $\beta$ as low as we have found for the dpAGB sources; their lowest value is $\beta = 0.87$ for cold 3 cm grains, for which they give $\chi_\nu(0.85 \text{ mm}) = 0.23 \text{ cm}^2 \text{ g}^{-1}$.

Significantly larger values of the dust emissivity at $\sim 1$ mm have been used in the literature, e.g., Jura et al. (1997) assume $\chi_\nu(1.3 \text{ mm}) = 3 \text{ cm}^2 \text{ g}^{-1}$ for the carbon-rich grains in the PPN, the Red Rectangle. Dasyra et al. (2005) find $\chi_\nu(0.85 \text{ mm}) = 1.4 \text{ cm}^2 \text{ g}^{-1}$ from detailed modeling of the SED of three spiral galaxies. Quoting similar results from studies of (1) high-latitude Galactic interstellar regions by del Burgo et al. (2003), (2) protostellar-core grains with ice mantles by Ossenkopf & Henning (1994), and (3) the spiral galaxy M51 by Meijerink et al. (2005), they argue for an enhanced emissivity at submm wavelengths. We derive conservative mass estimates, adopting $\chi_\nu(0.85 \text{ mm}) = 1.4 \text{ cm}^2 \text{ g}^{-1}$. The dust temperature is assumed to be $T_d = 50 \text{ K}$ for IRAS22036 (based on the detailed modeling by Sahai et al. 2006) and $T_d = 150 \text{ K}$ for the dpAGB sources (based on the detailed modeling by Gieles et al. 2007). The derived dust masses are inversely proportional to the dust emissivity and temperature, hence easily scaled to different values of these parameters.

In summary, our pilot EVLA survey confirms our hypothesis of large grain emission for two key pAGB objects, and thus it is likely to be applicable to these as a class—however, much more sensitive surveys of larger target samples at submm/mm and cm wavelengths are needed to establish it definitively. Current and upcoming facilities such as CARMA, ALMA, and the EVLA will allow such surveys to be carried out with fairly modest integration times. We have proposed new observations with the EVLA which already allows a factor eight larger continuum bandwidth (2 x 1 GHz compared to 2 x 128 MHz in our pilot survey), and will be significantly larger once the EVLA project is completed.

R.S.’s contribution to the research described here was carried out at the Jet Propulsion Laboratory, California Institute of
Technology, under a contract with NASA. Financial support was provided by NASA through a Long Term Space Astrophysics award (to R.S. and M.M.).

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