The Galactic Disk Distribution of Planetary Nebulae With Warm Dust Emission Features: I

S. Casassus\textsuperscript{1,2}, P. F. Roche\textsuperscript{1}, D. K. Aitken\textsuperscript{3} & C. H. Smith\textsuperscript{4}

\textsuperscript{1} Astrophysics, Physics Department, Oxford University, Keble Road, Oxford OX1 3RH
\textsuperscript{2} Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile.
\textsuperscript{3} Department of Physical Sciences, University of Hertfordshire, Hatfield, Herts AL10 9AB
\textsuperscript{4} School of Physics, University College, UNSW, Canberra, ACT 2600, Australia.

Accepted ... Received ...

ABSTRACT
We investigate the galactic disk distribution of a sample of planetary nebulae characterised in terms of their mid-infrared spectral features. The total number of galactic disk PNe with 8–13\textmu m spectra is brought up to 74 with the inclusion of 24 new objects, whose spectra we present for the first time. 54 PNe have clearly identified warm dust emission features, and form a sample which we use to construct the distribution of the C/O chemical balance in galactic disk PNe. The dust emission features complement the information on the progenitor masses brought by the gas-phase N/O ratios: PNe with unidentified infrared emission bands have the highest N/O ratios, while PNe with the silicate signature have either very high N enrichment or close to none, and SiC emission features coincide with a range of moderate N-enrichments. We find a trend for a decreasing proportion of O-rich PNe towards the third and fourth galactic quadrants. Two independent distance scales confirmed that the proportion of O-rich PNe decreases from 30±9\% inside the solar circle, to 14±7\% outside. PNe with warm dust are also the youngest. PNe with no warm dust are uniformly distributed in C/O and N/O ratios, and do not appear to be confined to C/O\sim1. They also have higher 6 cm fluxes, as expected from more evolved PNe. We show that the \textit{IRAS} fluxes are a good representation of the bolometric flux for warm-dust PNe. The requirement \( F(12\textmu m) > 0.5\text{ Jy} \) should probe a good portion of the galactic disk, and the dominant selection effects are rooted in the PN catalogues.

Key words: planetary nebulae: general – infrared: ISM: lines and bands – ISM: abundances.

1 INTRODUCTION
Spectroscopy at 10\textmu m has brought significant information on the chemical composition of planetary nebulae (PNe). The dust signatures reflect the C/O chemical balance at the tip of the asymptotic giant branch (AGB). In this article we use the 8–13\textmu m dust signatures as a systematic tool to investigate the distribution of the C/O abundance ratio in PNe. We classify the 8–13\textmu m spectral signatures in a sample consisting of compact and IR-bright PNe in the Strasbourg-ESO catalogue (Acker et al. 1992). The sample excludes PNe traditionally associated with the galactic bulge, which will make the object of a forthcoming article.

The family of emission bands usually referred to as the ‘unidentified infrared bands’ (UIR bands), with principal members at 3.3\textmu m, 6.2\textmu m, 7.7\textmu m, 8.6\textmu m and 11.3\textmu m, were first observed in the mid-IR towards NGC 7027 by Gillett et al. (1973). Cohen et al. (1986, 1989) found good correlations between the strengths of all pairs of bands towards a sample of PNe, reflection nebulae and HII regions, showing that they correspond to a generic spectrum. The strength of the 7.7\textmu m feature relative to the total \textit{IRAS} flux correlates strongly with the gas phase C/O ratio in a sample of 6 PNe (Cohen et al. 1986), and Duley & Williams (1981) identified the principal wavelengths of the UIR bands with transitions in the chemical functional groups of aromatic molecules. Polycyclic aromatic hydrocarbons are the commonly accepted carriers for the UIR bands (Léger & Puget 1984). Thus, although their exact carriers still remain to be determined, the UIR bands are indicative of a carbon rich environment.

The 8–13\textmu m spectra of PNe can also show signifi-
significant continuum emission attributed to ‘warm’ dust at \( \sim 200\)K. As first shown by Aitken et al. (1979), a smooth emission
feature with a peak at about 9.7\( \mu \)m is observed in the PNe SwSt 1, M1-26 and Hb 12. The peak of emission
coincides with the Si-O stretch in silicates (Day 1979, 1981), and this feature is similar to amorphous
condensates of silicate materials (Day and Domn 1978).

It is typical of the Trapezium region in Orion and of the circumstellar shells of some oxygen-rich stars (For-
rest et al. 1975), and is also seen in absorption towards the BN infrared point source in Orion (Gillet et al.
1975). Willner et al. (1979) detected a smooth emission
feature with a rather flat profile, from 10.5\( \mu \)m to about
12.7\( \mu \)m, towards the PNe IC 418 and NGC 6572. It is
commonly observed towards C stars as excess emission
over a black body spectrum, and is attributed to lattice
vibrations in silicon carbide (Forrest et al. 1975). An-
derson et al. (1999) published the mid-IR transmission
spectrum of meteoritic SiC grains; they obtained a good
match to the C star feature when extracting grains with
a small size distribution (i.e. < 5\( \mu \)m).

There are thus significant compositional differences
in the dust content of PNe, which can be classified
into dust emission types, and according to whether they
contain O-rich or C-rich grain materials (Aitken et al.
1979). How do the 10\( \mu \)m dust emission features compare
with the gas phase abundances? What is the proportion
of PNe that show each type of dust emission, and does
their distribution show large scale variations across the
galactic disk? It has been shown by Thronson et al.
(1987) and Jura et al. (1989) that the proportion of C
stars relative to M giants increases outside the solar
circle, and it is interesting to investigate whether PNe
follow a similar trend. In contrast to the C and M stars
which span a range of locations in the giant branch, PN
compositions reflect the surface abundances at the end
of the AGB, with a well defined evolutionary status.

This article is the first of a series devoted to the sta-
tistical analysis of the grain composition in galactic disk
PNe. In Section 2 we present a sample of 74 PNe with
8-13\( \mu \)m spectra, which includes 24 previously unpub-
lished spectra obtained with CGS3 on UKIRT or the
UCL spectrometer on UKIRT or the AAT. Section 2
also contains a brief description of the method used
to classify the 10\( \mu \)m continua (following Aitken et al.
1979). We will then compare in Section 3 the dust con-
tent of PNe with their gas phase C/O and N/O abun-
dance ratios, to show that the dust emission types rep-
resent an alternative for determining the C/O chemical
balance and bring complementary information on the
PN progenitors. The sky distribution of PN dust types is
presented in Section 4. After adopting a statistical
distance scale in Section 5, we will test in Section 6
the size of the PN sample in this work for stratification
in Peimbert (1978) types, and discuss its homogeneity,
giving some support for its statistical significance. The
galactic disk distribution of the PN dust composition is
presented in Section 7. Section 8 summarises our con-
clusions.

## 2 8–13\( \mu \)m SPECTROSCOPY OF COMPACT
AND INFRARED-BRIGHT PNE

The criteria for selection of the PN sample were that
they be compact, less than 10\( \arcsec \) in diameter so that
most of the flux is contained in the spectrograph beam,
and infrared bright, with IRAS 12\( \mu \)m flux in excess of
0.5 Jy. These criteria select the best candidates for the
detection of the dust emission features. A sample of
10 PNe was observed with CGS3 on UKIRT on 1996
September 27 and 28, with the intention of increasing
the number of objects measured beyond the solar circle.
An observing log is presented in Table 1 where details of
the previously unpublished spectra from the AAT and
UKIRT are listed. Both CGS3 and the UCLS were used
in their low-resolution modes, producing oversampled
spectra which are calibrated with respect to standard
stars. Fluxes are accurate to 20\%. The fluxes of emission
lines present in some objects are listed in table 2. Al-
though they provide information on the ionized gaseous
component, we will not use the emission lines for the
purpose of this work. The resulting spectra are shown
in Figure 1, together with fits to the 8-13\( \mu \)m continua
based on the grain emissivities, which form the basis of
the dust type classification.

We classified the type of dust emission features
according to the procedure described in Aitken et

\[\text{Table 1: Log of observations.}\]

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Date</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKIRT+CGS3</td>
<td>May 94</td>
<td></td>
</tr>
<tr>
<td>UKIRT+UCLS</td>
<td>Oct 87</td>
<td></td>
</tr>
<tr>
<td>UKIRT+CGS3</td>
<td>Sep 96</td>
<td></td>
</tr>
<tr>
<td>UKIRT+UCLS</td>
<td>Jul 90</td>
<td></td>
</tr>
<tr>
<td>UKIRT+CGS3</td>
<td>Sep 96</td>
<td></td>
</tr>
<tr>
<td>UKIRT+UCLS</td>
<td>Oct 87</td>
<td></td>
</tr>
<tr>
<td>UKIRT+CGS3</td>
<td>Sep 96</td>
<td></td>
</tr>
<tr>
<td>UKIRT+UCLS</td>
<td>Oct 87</td>
<td></td>
</tr>
<tr>
<td>AAT+UCLS</td>
<td>Apr 87</td>
<td></td>
</tr>
<tr>
<td>AAT+UCLS</td>
<td>Apr 86</td>
<td></td>
</tr>
<tr>
<td>AAT+UCLS</td>
<td>Apr 86</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Emission line fluxes, in $10^{-15}$W m$^{-2}$.

<table>
<thead>
<tr>
<th></th>
<th>[Ar III]</th>
<th>[S IV]</th>
<th>[Ne II]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.99 µm</td>
<td>10.52 µm</td>
<td>12.81 µm</td>
</tr>
<tr>
<td>NGC6578</td>
<td>2.10</td>
<td>17.0</td>
<td>—</td>
</tr>
<tr>
<td>M1-71</td>
<td>3.57</td>
<td>5.52</td>
<td>2.27</td>
</tr>
<tr>
<td>Hen2-447</td>
<td>1.04</td>
<td>—</td>
<td>5.98</td>
</tr>
<tr>
<td>K3-53</td>
<td>—</td>
<td>2.56</td>
<td>—</td>
</tr>
<tr>
<td>K3-52</td>
<td>—</td>
<td>2.45</td>
<td>1.00</td>
</tr>
<tr>
<td>M3-35</td>
<td>—</td>
<td>4.77</td>
<td>1.99</td>
</tr>
<tr>
<td>Hn1-2</td>
<td>—</td>
<td>1.93</td>
<td>—</td>
</tr>
<tr>
<td>M1-77</td>
<td>—</td>
<td>—</td>
<td>0.98</td>
</tr>
<tr>
<td>M2-49</td>
<td>—</td>
<td>2.29</td>
<td>—</td>
</tr>
<tr>
<td>K3-62</td>
<td>1.16</td>
<td>2.36</td>
<td>0.58</td>
</tr>
<tr>
<td>K3-60</td>
<td>—</td>
<td>2.27</td>
<td>—</td>
</tr>
<tr>
<td>M2-54</td>
<td>—</td>
<td>0.63</td>
<td>0.90</td>
</tr>
<tr>
<td>M1-4</td>
<td>—</td>
<td>9.52</td>
<td>—</td>
</tr>
<tr>
<td>IC2149</td>
<td>—</td>
<td>—</td>
<td>2.02</td>
</tr>
<tr>
<td>M1-14</td>
<td>0.89</td>
<td>—</td>
<td>1.33</td>
</tr>
<tr>
<td>Hen2-117</td>
<td>4.03</td>
<td>13.9</td>
<td>3.92</td>
</tr>
<tr>
<td>Hen2-142</td>
<td>—</td>
<td>11.8</td>
<td>—</td>
</tr>
<tr>
<td>Pe1-7</td>
<td>—</td>
<td>—</td>
<td>22.5</td>
</tr>
</tbody>
</table>

(1) and Aitken and Roche (1982). The emissivity functions $\epsilon_i$ for the three types of grains are taken from the spectra of astrophysical sources, with $F_\lambda = \epsilon_i B(\lambda, T)$, where $F_\lambda$ is the observed flux density and $B(\lambda, T)$ is a Planck function at temperature $T$ ($\epsilon_i$ is then fixed by $\epsilon_i(10\mu m)=1$). Additionally a smooth continuum with emissivity $f(\lambda) \propto \lambda^{-1.8}$, which is taken to represent graphite grains (or amorphous carbon grains), was included in the fitting procedure. The relative contribution of emissivity functions and the temperatures of the grains are fit to the 8-13µm continua following a $\chi^2$ minimisation:

$$F_\lambda = \sum a_i\epsilon_i(\lambda)B(\lambda, T_i)/B(10\mu m, T_i),$$

(1)

$$\chi^2 = \sum \frac{(F^{\text{obs}}_\lambda - F_\lambda)^2}{\sigma^2_{\chi}},$$

(2)

where the sum extends to the number of dust components used in the fit, and $\epsilon_i$ stands for the error in each point of the observed spectrum $F^{\text{obs}}$. The Planck functions are arbitrarily normalised at 10µm. Best fit values are thus obtained for the measure of contribution of each emission type $a_{1-4}$, and their black body temperatures $T_{1-4}$. The relative contribution of each dust type is $a_i' = a_i/\sum a_j$, summing over all the dust types required in the fit. The coefficient $a_i'$ is thus a representation of the fractional emission at $\lambda=10\mu m$. The fitting procedure assumes that all emitting materials are optically thin and that any absorption occurs in a cold foreground layer; in the case of absorption a factor $e^{-\tau(\lambda)}$ is included in Eq. 2 ($\tau(\lambda)$ is the wavelength dependent opacity, with a profile given by the emissivity curve, keeping $\tau(10\mu m)$ as a free parameter). The available data provide insufficient constraints to warrant a more detailed radiative transfer treatment.

As discussed in Aitken and Roche (1982), it is the silicate grain emission feature that really separates PNe into different groups. A portion of PNe with silicate emission also show the UIR bands, and sometimes require SiC in small amounts. Graphite emission seems to be unrelated to the other types of grains. The PN dust signatures can be placed into four groups based on the dominant dust species at 10 µm as shown in Table 3.

A list of all the identified dust emission features found in this sample of PNe can be found in Table 4. The S/N ratio of many spectra are rather low, and higher quality data may confirm the need for mixture of grain types. However, in this article we are concerned with the dominant material. The column under ‘comments’ gives more information on the best fit parameters, in the form

$$(\text{grain type}) : a', T, \tau,$$

(3)

where the optical depth field $\tau$ is listed for only when absorption is required (which is the case for M 2-9, M 2-56 and 19w32).

As would be expected from blackbody radiation between 8-13µm, a typical dust temperature is $\geq 200K$, and the 8-13µm dust emission can be referred to as ‘warm dust emission features’ in comparison with colder dust $\leq 200K$ which makes the bulk of the FIR emission (e.g. Kwok et al. 1986).

The objects are listed in the Strasbourg-ESO catalogue (Acker et al. 1992) as ‘true or probable’ PNe. The exception is IRAS 21282+5050, whose optical spectrum (Cohen & Jones 1987) shows [O III] emission lines, photospheric absorption features corresponding to a heavily reddened [WC11] nucleus, and a total luminosity of about $2 \times 10^3 L_\odot$ for a guessed distance of 2 kpc, making it a probable low-excitation PN (the central star has been re-classified as an O star by Crowther et al. 1998).

In the notation of Table 3, out of 74 galactic disk PNe with 8-13µm spectra, there are 12 O nebulae (of which SwSt1 and IC4997 also show the UIR bands), 16 C nebulae and 26 C nebulae (for 9 of which the fits are improved with the inclusion of SiC). The remainder shows either too little continuum emission (17 PNe), or no clear identification in terms of the classification used here (e.g. IC2149 and M1-14 whose spectra are best fit-
Figure 1: 10μm spectra for the PNe listed in Table 1. In abscissae is the wavelength range in μm, and in ordinates the flux density in $10^{-19}$ W cm$^{-2}$ μm$^{-1}$. A fit to the continuum emission is shown for the spectra with identified dust features, with parameters listed in Table 4. The data points around bright emission lines ([AIII], [SIV] and [NeII] at 8.99, 10.52 and 12.81 μm respectively) are excluded from the fits.
Landscape Table to go here

Table 4:
ted by graphite emission only, and K4-57, whose spectrum is flat in units of Janskys, and is atypical of PNe). Finally the fits in Hb12 and Vy2-2, both classified as ‘O’ PNe, require some amount of SiC, which is probably due to variations in the silicate emission profile rather than a superposition of grain types.

3 COMPARISON OF THE DUST COMPOSITIONS AND THE GAS PHASE ABUNDANCES

How does the warm dust emission feature classification, based on the grain C/O chemical balance, compare with the gas phase C/O abundance ratios? How does it compare to nitrogen enrichment? In order to address these questions, we searched the literature for published gas phase abundances in PNe with 8-13 µm spectra. Table 4 lists the PNe for which a detailed spectroscopic analysis is available, but it should be borne in mind that the uncertainties in the abundance analysis are often substantial. The PNe are classified according to the Peimbert (1978) types, with the sub-types in N/O ratio introduced by Faúndez-Abans & Maciel (1987). Many assignments to N/O types are taken from the compilation in Maciel & Dutra (1992).

Figure 2 shows the distribution of gas phase C/O ratios for each 8-13 µm continuum class. The correspondence is not direct, some nebulae with C based grains have gas phase C/O<1. There is however a good correlation in C based grains with C/O ratio, previously obtained by Barlow (1983) and Roche (1989), for example, but with a lower number of PNe. Silicate grains indicate an O rich environment, SiC a C rich environment, and the UIR bands correlate with a strong over-abundance of C relative to O. Weak continuum PNe are widely spread in C/O ratios, suggesting they may correspond to later evolutionary stages, rather than C/O~1. It is established that the dust composition reflects on average the gas phase composition, and can be used as probes of C enrichment in PNe. The warm dust features are thus an alternative to the UV lines [C ii] λ2326, [C iii] λ1908, [C iv] λ1550, for coarse classifications of C/O ratios.

The existence of 5 PNe with C/O<1 and grain emission characteristic of C rich environments merits further attention. The same apparently paradoxical situation is hinted at by the superposition of silicates and C based grains in the spectra of SwSt1, IC4997, Hb12 (confirmed by measurements at 3 µm showing the 3.3 µm UIR band, Roche et al. 1996). Standard equilibrium chemistry suggests the least abundant of C or O would be locked in CO (Gilman 1969), and the production of C-rich molecules in O-rich circumstellar environments may be a rather rare nonequilibrium phenomenon (observed towards certain M supergiants in h and χ Per, Sylvester et al. 1998). This is also suggested by the appearance of both C- and O-type grains in novae (e.g. Smith et a. 1995). Thus mixtures of grain types imply either a stratification in the ejecta composition of the progenitor star, or the mixing of the progenitor ejecta with pre-existing material. This point is relevant when linking the grain types with the C/O ratios of the progenitor stars, and will be discussed further in a forthcoming article (Casassus & Roche 2000, paper II).

The link between the dust types and N enrichment is shown in Figure 3. The UIR bands are found mostly in nebulae of Peimbert type I, whereas SiC emission and ‘weak’ continuum PNe are uniformly represented. Silicates are found either with strong N enrichment (type I), or none at all (types Ib and III). These trends should be confirmed with a larger sample of objects with known N/O ratios, especially for O-type signatures.

The stratification of PNe in N/O ratios with height above the galactic plane suggests that the Peimbert classification is indicative of progenitor mass. Thus, on a relative mass scale, the UIR bands correspond to higher progenitor masses, SiC to intermediate masses, silicates are found mainly for low mass progenitors, but also for the most massive ones. The uniform distribution of ‘weak’ continuum PNe again suggests they may correspond to later evolutionary stages.

But the dichotomy between O- and C-type PNe for high gas phase N/O abundance ratios indicates that there is no simple correspondence between progenitor mass and dust signature. The dust emission features provide complementary information to the Peimbert types.
8.5cm!

Table 5: The properties of the sky distribution of planetary nebulae dust types. The errors quoted correspond to one standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>( &lt;b&gt; ) [degrees]</th>
<th>( b_{\text{rms}} ) [degrees]</th>
<th>( N )</th>
<th>( l &lt; 90 )</th>
<th>( 90 &lt; l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>-1.6±2.3</td>
<td>8.0±1.6</td>
<td>12</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>c</td>
<td>-3.3±2.0</td>
<td>7.9±1.4</td>
<td>16</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>-0.4±0.8</td>
<td>4.1±0.6</td>
<td>26</td>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td>+</td>
<td>6.6±3.5</td>
<td>15.5±2.5</td>
<td>20</td>
<td>12</td>
<td>8</td>
</tr>
</tbody>
</table>

There is a hint of a decrease in the proportion of silicate grains PNe from the first and fourth quadrants \((-90 < l < 90)\) to the second and third quadrants \((90 < l < 270)\), from 0.25±0.07 to 0.17±0.09. Since it corresponds to only one \( \sigma \) it cannot be considered a solid property of the distribution. There is also an indication of an increase in the relative proportion of SiC PNe, which doubles from 0.22±0.07 to 0.44±0.11.

5 ADOPTED DISTANCE SCALES

5.1 Distance scales based on 6 cm continuum emission

One of the persistent problems related to the study of PNe is the difficulty of obtaining accurate distances. A review of the methods based on individual properties of PNe can be found in Peimbert (1992). These so-called ‘direct’ distance estimators are available for a restricted number of objects, and suffer from intrinsic uncertainties. However, the distances to PNe can be determined on a statistical basis, which match the average properties of PNe. A distance scale for PNe can be built on the assumption that a general relationship holds for a set of PNe. We adopted the distance scale derived by Zhang (1995), who used an arithmetic average of two complementary methods, one based on the mass-radius relationship (e.g. the review by Kwok 1994), and the other on the relationship between \( T_b \), the free-free 6 cm brightness temperature, and nebular radius (as introduced by Van de Steene & Zijlstra 1994). Zhang (1995) calibrated the mass-radius and \( T_b \)-radius relationships with a large sample of PNe with individually and ‘directly’ determined distances. This ‘direct’ method is explained in detail in Zhang and Kwok (1993) and Zhang (1993), and depends on the distance-independent parameters \( T_b \) and the central star temperature \( T_\star \). Distances thus obtained are strongly model dependent, and can be in disagreement with the more accurate comparison of angular expansion rate and radial velocity. NGC 6572, NGC 6302, NGC 3242, NGC 2392, and NGC 7662 are given ‘direct’ distances of, respectively, 2.9 kpc, 0.1 kpc, 1.1 kpc, 0.5 kpc, 1.6 kpc, while their ex-
pansion distance is $1.5 \pm 0.5$, $1.6 \pm 0.6$ kpc, $0.4 \pm 0.1$ kpc, $>1.4$ kpc, $0.8 \pm 0.7$ kpc (Gomez et al. 1993, Hajian et al. 1995, Hajian & Terzian 1996). But the details of the distances to each nebula is of secondary importance as long as the global properties of PNe are reproduced. In that sense, the Zhang (1995) distance scale gives a Gaussian distribution about the galactic centre for bulge PNe, with a narrower scatter than the scale by Van de Steene & Zijlstra (1994).

5.2 Distances from IRAS fluxes to optically thick PNe

As the central stars of PNe evolve rapidly in time, and the nebulae are active radiatively and dynamically (e.g. Kwok 1994), distance scales based on invariant properties of PNe cannot be applied to the whole PN population. But in the case of the sample discussed here, the 4 IRAS band fluxes, coupled with constant luminosity, may provide an alternative distance scale, as we now argue.

The compact and IR-bright PNe are likely to be young, surrounded by substantial molecular material and therefore optically thick to the ionizing radiation from the central star. In this case the total luminosity of the nebulae can be inferred from the flux of any HI recombination line, by equating the number of H$^+$ recombinations to the number of photoionizations. Méndez et al. (1992) tested this hypothesis by comparing with spectroscopic studies of PN nuclei, linking the surface gravity and effective temperature to the luminosity through atmosphere models. Their conclusion is that most PNe are optically thin. However, their sample is biased against obscured central stars: out of 23 PNe, 6 are infrared-bright and are among the sample discussed here, 4 of which have no warm dust. Thus Méndez et al. (1992) included only two nebulae with 8–13 μm spectra showing warm dust emission, for which the ratio of luminosities derived from optical thickness to the model-atmosphere luminosities are 0.70 and 0.92 (for M1-26 and IC418). It is thus likely that the compact and IR-bright PNe with warm dust emission are optically thick.

In PNe which are optically thick in the Lyman continuum, the ionized central regions are surrounded by substantial amounts of neutral gas, an environment favourable to dust-grain survival. Most of the UV radiation escaping from the ionized region would be absorbed by dust grains, which heat up as a result to $\sim 100$–200 K, and re-radiate in the mid- and far-IR spectral range. The IRAS band fluxes should give a good representation of the bolometric fluxes using

$$ F_{\text{IRAS}} = \sum_{j=1}^{4} \nu L_\nu(j), $$

(4)

where the sum extends to the 4 IRAS bands.

PNe initially evolve at a constant luminosity once they leave the AGB, as was first shown by Paczyński (1970, see also Blöcker 1995). The luminosity function for the youngest PNe should be close to that of tip-of-the-AGB objects. The distribution of core masses for stars at the tip of the AGB can be calculated with a synthetic AGB model and a crude galactic disk model (we used the analytic prescriptions in Groenewegen & de Jong 1993, and a galactic disk model described in paper II). The core-mass luminosity relationship from Wagenhuber & Groenewegen (1999), in the case of post-AGB objects (i.e. in the asymptotic regime and vanishing envelope mass), gives the luminosity function of young PNe* shown in Figure 5a, with a mean of 8500 L$_\odot$. A very similar luminosity function, with an average of 9300 L$_\odot$, is obtained using the prescriptions in Wagenhuber & Groenewegen (1999) for the initial-final mass and core-mass-luminosity relations, and taking solar metallicity and an IMF index of 1 (instead of 1.72 in paper II, in a notation where the Salpeter (1955) IMF would be 1.35), with a constant star formation rate.

It appears the PN luminosities are not expected to vary over more than one order of magnitude. Assigning the same luminosity of 8500 L$_\odot$ for all PNe gives a maximum error on the distance of only a factor $\lesssim 2$. Distances to compact and IR bright PNe can thus be estimated under the assumption of constant luminosity. Eq. 4 for the bolometric flux is likely to be a lower limit only, but in this article we are interested in the relative properties of the distribution of the different PNe dust types, and their absolute distances are not required. We will refer to distances derived in this way by $D_{\text{IRAS}}$, and those from Zhang as $D_{2\beta5}$.

We stress $D_{\text{IRAS}}$ distances are only meant to investigate an independent distance scale and its conse-

Figure 5: a) Synthetic PN luminosity function from the initial-final mass relationship of Groenewegen & de Jong (1993), and with progenitor ZAMS masses between 1.2 and 7 M$_\odot$. b) The relationship between $D_{\text{IRAS}}$ and Zhang (1995) for the PNe with warm dust emission.

* PNe progenitors for the sample discussed here were assumed to have masses in the range 1.2<M/M$_\odot$<7, see paper II.

© 2000 RAS, MNRAS 000, 1–12
quences on the derived galactocentric trends; these distances should not be taken as accurate.

### 5.3 Adopted distances to compact and IR-bright PNe

The distances derived from the two methods described above are listed in Table 4. \(D_{\text{IRAS}}\) distances appear to be reasonable for PNe with detected warm dust emission. Figure 5b shows a good correlation between the two distance estimates in the case of PNe with warm dust emission: The ratio \(D_{\text{IRAS}}/D_{\text{Z95}}\) is 1.87 on average, with a 1-\(\sigma\) spread of 0.84. This suggests that the luminosity used to derive \(D_{\text{IRAS}}\) distances may be overestimated by a factor \(\sim 3 - 4\), if \(D_{\text{Z95}}\) distances are reliable. Also, the cases of NGC 6302, NGC 6572 and BD+30\(^{3}\)3639 (three PNe with warm dust emission features) allow comparing their expansion distances of 1.6 kpc, 2.9 kpc and 2.12 kpc. Although the comparison supports \(D_{\text{IRAS}}\) distances, a handful of objects does not permit a generalization. In any case, \(D_{\text{IRAS}}\) may be used as an upper limit, except for PNe with upper limits in the \(\text{IRAS} 100 \mu \text{m}\) band. It is worth noting, however, that the PNe V\(\nu\)2-2, IRAS21282+5050, Hb12 and Hen2-113 are given distances on the Zhang (1995) scale that are in excess of \(D_{\text{IRAS}}\) by a factor larger than 1.7 (which takes into account the maximum range expected in the PN luminosity function).

In the remainder of this article we assign \(D_{\text{IRAS}}\) distances to PNe without radio data (i.e. M2-56 and HDE330036). The case of K\(3\)-69 seems to be anomalous: both distance estimates give \(\sim 25\) kpc, putting K\(3\)-69 at 1.7 kpc above the galactic plane, and we preferred to use the distance of 7.9 kpc from Cahn et al. (1992). Another anomalous case is M2-54: again, the Zhang (1995) distance scale and \(D_{\text{IRAS}}\) both give a distance of \(\sim 13\) kpc, placing it near the northern galactic warp. In order to avoid the uncertainties associated with exaggeratedly large distances, we adopted a maximum galactocentric radius of 14 kpc to compute the moments of the vertical distribution, thus excluding K\(3\)-69 and M2-54.

### 6 TESTS FOR THE COMPLETENESS AND HOMOGENEITY OF THE COMPACT AND IR-BRIGHT PN SAMPLE

The sequence in Peimbert (1978) types is indicative of progenitor mass, the highest being associated with type I. There is a stratification in height above the galactic plane as a function of N/O type (e.g. Maciel and Dutra 1992). Such a stratification is indeed present in this sample. Inside the solar circle, the root mean square height over the plane, \(z_{\text{rms}}\), is 0.14 kpc for type I, 0.37 for type IIa, 0.45 for type IIb, and 0.68 for type III. This stratification is an indication that a statistical study based on the compact and IR-bright PN sample would be sensitive to PN properties with the same dependence on progenitor mass as the Peimbert types. Out of 49 compact and IR-bright PNe with known N/O ratio, 29\(\pm\)6\% are type I, 21\(\pm\)6\% are type IIa, which is typical of PN catalogues (e.g. Maciel & Dutra 1992). The disk PN population seems to be homogeneously sampled, although the constraints will remain loose until a larger sample is available.

A discussion of the selection effects is possible in terms of a comparison between the fraction of O-rich PNe and the predictions of synthetic AGB models. In paper II we compare expected tip-of-the-AGB statistics for the C/O chemical balance with those from the dust signatures. We find that for a minimum PN progenitor mass of 1 M\(_{\odot}\), about 50\% of all young PNe should be O-rich, whereas we report 22\%. To match the observed ratio, the minimum PN progenitor mass for the sample in this work must be at least \(M_{\text{min}}\)\(=1.2\), at a 2\(\sigma\) confidence level - assuming the warm dust composition corresponds to the last \(\sim 2000\) yr of AGB evolution. Averaging the AGB ejecta over the last 25\(000\) yr increases the fraction of O-rich PNe by \(\sim 10\%\), which may explain the higher frequency of O-rich nebulae with plasma diagnostics (40 \(\pm\) 8\% in the sample used here).

It is possible, however, that differences in the opacity functions among C- or O-based grains could lead to different lifetimes of the warm-dust emission phase. In this case the tip-of-the-AGB and observed C/O statistics would be different. To summarise, the maximum separation from the central star, \(r_{0}\), required to keep a dust grain at a temperature \(T > T_{0}\) is \(r_{0} \propto \sqrt{k_{s}/k_{T}}\), where \(k_{s}\) is the opacity averaged over the central star spectrum, and \(k_{T}\) is averaged over a black body at \(T_{0}\). For instance, it may be thought that if C-rich grains have higher \(k_{s}/k_{T}\) than O-rich grains, then the C-rich warm-dust phase would be longer. But either A) \(k_{T}\) is fixed, and then the acceleration of C-rich grains by UV-radiation pressure would be higher, thereby shortening the C-rich warm-dust phase, or B) \(k_{s}\) is fixed and \(k_{T}\) is lower for C-rich grains, in which case the 10\(\mu\)m fluxes of C-rich PNe would be lower, limiting the number of C-rich PNe in spite of their hypothetical extended lifetimes. In addition the role of the stellar wind and the interaction with the nebula considerably complicate the picture.

But a test can be found for the preferential selection of O- or C-rich grains. The good agreement between \(D_{\text{IRAS}}\) and \(D_{\text{Z95}}\) suggests Eq. 4 can be used to estimate the fraction of luminosity radiated in the 12\(\mu\)m \(\text{IRAS}\) band by PNe with warm dust emission, with

\[
\frac{L_{12\mu m}}{L_{\star}} = \frac{\nu I_{\nu}(12\mu m)}{\sum_{j=1}^{4} \nu I_{\nu}(j)}.
\]

Omitting the PNe with upper limits in the 100\(\mu\)m \(\text{IRAS}\)
band, the fraction of luminosity emitted at 12\(\mu\)m is
\(\sim 0.25 \pm 0.15\) for PNe with silicate emission, 0.22\(\pm\)0.09 for SiC PNe, 0.27\(\pm\)0.14 for UIR PNe, and \(\sim 0.25 \pm 0.14\) for all warm dust types, while ‘weak’ PNe have a
\(L_{12\mu m}/L_*\) ratio of 0.11\(\pm\)0.03 (this sample is biased towards high values of \(L_{12\mu m}/L_*\), so the average for all PNe would be much lower). Considering the relatively large uncertainties, the above values show that, for a given central star luminosity, the IR-bright selection criterion would not preferentially select one type of grains given central star luminosity, the IR-bright selection criteria of compact angular size, explains why they are on average closer. It is thus very likely that PNe with weak continuum correspond to later evolutionary stages, and are not a transition stage where C/O\(\sim\)1. Although \(D_{IRAS}\) distances are not applicable to ‘weak’ PNe, whose optical thickness is uncertain, it is interesting to note that the average \(D_{IRAS}\) distance to ‘weak’ PNe is 9.0 kpc, greater than for any other type of PNe. This could be interpreted as a lower average luminosity (as expected for more evolved PNe on the white dwarf cooling track), or that for ‘weak’ PNe the far-IR flux \(F_{IRAS}\) is not a good approximation to the bolometric flux.

Table 6: The properties of the distribution of PN dust types, based on the distances from Zhang (1995). The errors quoted correspond to one standard deviation.

<table>
<thead>
<tr>
<th>(D/D_{rms})</th>
<th>(&lt; z &gt;)</th>
<th>(z_{rms})</th>
<th>(N)</th>
<th>(&lt; R_0)</th>
<th>(&gt; R_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[kpc]</td>
<td>[100 pc]</td>
<td>[100 pc]</td>
<td>(&lt; R_0)</td>
<td>(&gt; R_0)</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>3.9/2.1</td>
<td>-1.0(\pm)1.4</td>
<td>(4.7\pm1.0)</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>c</td>
<td>4.3/2.0</td>
<td>-1.8(\pm)1.0</td>
<td>(4.1\pm0.7)</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>C</td>
<td>3.8/2.3</td>
<td>-0.0(\pm)0.5</td>
<td>(2.3\pm0.3)</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>+</td>
<td>2.3/1.0</td>
<td>2.3(\pm)0.9</td>
<td>(4.7\pm0.8)</td>
<td>19</td>
<td>10</td>
</tr>
</tbody>
</table>

There is a peculiar asymmetry in the face-on distribution of PNe of Figure 6. The sector of the galactic disk with southern galactic longitudes (the third and fourth quadrants) is underpopulated. This is an effect due simply to the incompleteness of the catalogues. The same asymmetry can be seen in the face-on map of Durand et al. (1998), with a larger number of PNe. Warm dust PNe with reliable IRAS fluxes all gather in very tight IRAS colour-colour boxes (in particular \(\log(F(100\mu m)/F(60\mu m))< 0, \log(F(25\mu m)/F(12\mu m)) > 0\)) which allows selecting all warm-dust PN candidates from the IRAS PSC. We found 331 IRAS point sources with colours of warm dust PNe, whose galactic longitude/latitude distribution is uniform from northern to southern longitudes. Also, the Carina spiral arm between the third and fourth quadrant is viewed tangentially from the sun, thus increasing the interstellar extinction and limiting the PN discovery rate.

8 CONCLUSIONS

The total number of PNe with 8–13\(\mu\)m spectra has been increased to 74 with the inclusion of 24 new objects. The sample consists of compact and IR-bright galactic disk PNe listed in the Strasbourg-ESO catalogue. 54
Table 7: Same as table 6, but with $D_{IRAS}$ distances.

<table>
<thead>
<tr>
<th></th>
<th>$D/D_{rms}$</th>
<th>$&lt;z&gt;$</th>
<th>$z_{rms}$</th>
<th>N</th>
<th>$&lt;R_o&gt;$</th>
<th>$R_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[kpc]</td>
<td>[100 pc]</td>
<td>[100 pc]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>4.0/1.6</td>
<td>-1.8±1.9</td>
<td>$6.2±1.3$</td>
<td>12</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>c</td>
<td>8.4/3.6</td>
<td>-4.6±2.7</td>
<td>$11.0±1.9$</td>
<td>16</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>C</td>
<td>5.6/3.2</td>
<td>-0.7±0.9</td>
<td>$4.4±0.6$</td>
<td>26</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 6: The galactic disk distribution of warm-dust PNe on a face-on view of the disk, with distances from Zhang (1995). Ticks are every 5 kpc, and the solar circle is shown in dashed line.

PNe have clearly identified warm dust emission features, which are placed into three groups (see Table 3): 12 PNe show silicate emission, 16 show SiC, and 26 show the UIR bands. The remainder have 8–13$\mu$m spectra dominated by emission lines, and correspond to later evolutionary stages. Thus 22±6% of the PNe with warm dust emission have O-rich grains. We have used this sample for an initial study of the PN dust emission features in the galactic context.

A comparison of the PNe dust types with the gas phase C/O ratio shows a good correspondence: Silicate nebulae have C/O<1, SiC nebulae are found with C/O≥1, while PNe that show the UIR bands often have C/O>>1. We thus confirm that the dust emission features represent an alternative to the plasma diagnostic for measuring the C/O chemical balance in PNe. Nebulae that show the UIR emission bands also have the highest N/O gas phase ratio. Silicate nebulae are found either with high N/O ratios, or no nitrogen enrichment at all. On the other hand SiC nebulae are more uniformly distributed in N/O ratios. Thus, on a relative mass scale, PNe with emission from the UIR bands correspond to higher progenitor masses, and those with SiC to intermediate masses. Silicates are found mainly for low mass progenitors, but also for the most massive ones. The dust emission features thus provide complementary information on the progenitors masses to the Peimbert types.

The adoption of statistical distances showed that the sample is large enough to show stratification in Peimbert types. We find a link between objects with UIR band emission and higher progenitor masses, as indicated by their concentration towards the galactic plane, obtained from their sky distribution and through the use of two independent PN distance scales. There is a trend for a decreasing proportion of O-rich PNe with galactocentric radius, confirmed by both distance scales, from 30±9% inside the solar circle, to 14±7% outside. This trend reflects the variations in the M/C star ratio from Thronson et al. (1987) and Jura et al. (1989).

We also showed that the IRAS fluxes are a good representation of the bolometric flux for PNe with warm-dust emission (Section 5). The requirement $F(12\mu m) > 0.5$ Jy should probe a good portion of the galactic disk, and the dominant selection effects are rooted in the PNe catalogues.

Although most known IR bright and compact PNe were included in this study, further observations are required to improve the statistics. Large aperture telescopes and mid-IR array detectors will be much more sensitive for the detection of the warm dust emission features in these compact objects, and could allow a more accurate analysis.
ACKNOWLEDGMENTS

We are grateful to the referee for interesting comments, and to PATT for the time allocation on UKIRT, which is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council, and PATT and ATAC for allocations on the AAT. S.C. acknowledges support from Fundación Andes and PPARC through a Gemini studentship.

REFERENCES

Casassus S., Roche P.F., 1999, submitted (Paper II)
Roche P.F., 1988, IAU symp 131 “Planetary Nebulae” ed S.Torres Peimbert, p117

This paper has been produced using the Royal Astronomical Society/Blackwell Science \LaTeX\ style file.